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Mounted Combat System Crew Shock Loading: Head and Neck Injury Potential Evaluation

by Michael E. LaFiandra and Harry Zywiol

ARL-TR-4170 **July 2007**

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Mounted Combat System Crew Shock Loading: Head and Neck Injury Potential Evaluation

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14. ABSTRACT The Future Combat System Mounted Combat System (MCS) is an assault vehicle that will employ a 120-mm weapon. The goal of this project was to quantify the effects of weapon fire recoil on a surrogate human occupant of the MCS. In March and April 2004, the U.S. Army Tank-Automotive Research, Development, and Engineering Center (TARDEC) ride motion simulator (RMS) was used to simulate the effects of gun firing shock on a Hybrid III instrumented anthropometric test device capable of measuring neck force and torque and head acceleration. The RMS was used to simulate the dynamic motion of two MCS crew positions during weapon firing scenarios: the driver and the gunner. Firing scenarios ranged in azimuth from 0 to 180 degrees and in elevation from -10 to 30 degrees. The raw data for this project were collected by the Motion Base Technologies Team of TARDEC and their contractors. The data were sent to the U.S. Army Research Laboratory's (ARL's) Human Research Engineering Directorate for analysis. Biomechanics researchers at ARL were tasked with relating the neck force and torque and head accelerations to establish injury criteria for the neck and head. Data from the Hybrid III manikin were compared to the standards established by the National Highway Traffic Safety Administration (NHTSA). Based on the standards used by NHTSA, the acceleration of the head and the forces and torques experienced by the driver's and gunner's necks during weapon firing are less than the injury criteria for the 50th percentile male. Resulting injury rates were nearly zero for head injuries but were as high as 0.13 (13%) for moderate neck injuries and as high as 0.023 (2.3%) for critical neck injuries. It is important to note that the injury criteria being applied are based on single impulse events, such as a vehicle hitting a tree, and are not necessarily appropriate for multiple impulse events such as repeated weapon firing, which is a major limitation of this study. Because of this and the fact that there may be a cumulative effect of repeated impulses on the probability of injury, the injury probabilities reported may be artificially low. At the time this report was written, a standard for multiple events had not been established.					
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Executive Summary

The Future Combat System Mounted Combat System (MCS) is an assault vehicle that will employ a 120-mm weapon. The goal of this project was to quantify the effects of weapon fire recoil on a surrogate human occupant of the MCS. The study took place in March and April of 2004. The U.S. Army Tank-Automotive Research, Development, and Engineering Center's (TARDEC's) ride motion simulator (RMS) was used to simulate the effects of gun firing shock on test manikins. The RMS was used to simulate the dynamic motion of two MCS crew positions during weapon firing scenarios: the driver and the gunner. The motion of the RMS was controlled, based on data recorded from a dynamic analysis design system simulation, provided to TARDEC by General Dynamics Land Systems. The driver's seat was facing forward in the vehicle, and the gunner was seated orthogonally to the driver. The state of the art of modeling is inadequate because models do not currently exist that have the required resolution to obtain the forces and torques needed for this analysis. Subsequently, an instrumented manikin was used for data collection instead of our relying solely on computer modeling of impulse and head movement.

A Hybrid III instrumented anthropometric test device capable of measuring neck force, torque, and head acceleration was placed in the seat of the RMS, and data were recorded from the manikin during the firing scenarios. Firing scenarios ranged in azimuth from 0 to 180 degrees and in elevation from -10 to 30 degrees. The raw data for this project were collected by the Motion Base Technologies Team of TARDEC and their contractors. The data were sent to the U.S. Army Research Laboratory's (ARL's) Human Research Engineering Directorate for analysis. Biomechanics researchers at ARL were tasked with relating the neck force, torque, and head accelerations measured by the Hybrid III instrumented manikin to established injury criteria for the neck and head. Data from the Hybrid III manikin were compared to the standards established by the National Highway Traffic Safety Association (NHTSA).

Specifically, the potential for neck injury was estimated on the basis of the N_{ij}, and the potential for head injury was estimated based on the head injury criteria (HIC). The N_{ij} is a measure of the axial and shear loads, as well as the bending moments, imposed on the neck. The HIC is the integral of accelerations over a given time period. In 1986, the appropriate time period was determined to be 36 ms, resulting in the HIC_{36}; however, in 2000, NHTSA proposed a change in the time period to 15 ms, resulting in $HIC_{15.}$

Based on the standards used by NHTSA, the acceleration of the head and the forces and torques experienced by the driver and gunner's neck during weapon firing are less than the injury criteria for the 50th percentile male. The injury criteria set by NHTSA indicate a 30% probability of a serious injury. The resulting probabilities of injury rates for the MCS were nearly zero for head injuries but were as high as 0.13 (13%) for moderate neck injuries and 0.023 (2.3%) for critical neck injuries. These injury probabilities indicate that a moderate neck injury will occur 13% of

the time the weapon is fired, and a critical neck injury will occur 2.3% of the time the weapon is fired. These results could be interpreted that a moderate neck injury could be expected once every 8 shots, and a critical neck injury would be expected once every 44 shots. The estimated probability of neck injury does not account for possible cumulative effects of the repeated impulses of the weapon firing. For instance, in a repeated impulse situation, each impulse may result in a micro-trauma to the neck structure or neck muscle fatigue that is below the threshold of what would be considered injurious; however, the micro-trauma may weaken the structure of the neck (or fatigue the neck muscles), resulting in an increased probability of injury in subsequent firings.

A major limitation to this work is that the injury criteria and probability for injury calculations being applied are designed for single impulse events instead of multiple impulse events (such as the repeated firing of the weapon). Because of this and the fact that there may be a cumulative effect of repeated impulses on the probability of injury, the injury probabilities reported may be artificially low. Although previous researchers have identified this as a limitation in their work (Hundley & Haley, 1987) and noted the need to establish human tolerance criteria for lower level impact accelerations, an exhaustive literature review did not uncover a standard for multiple events similar to the accelerations and forces experienced by the occupants of the MCS. This is a substantial limitation in the knowledge base that needs to be addressed through basic and applied research.

1. Project Background

The Future Combat System (FCS) Mounted Combat System (MCS) is an assault vehicle that will employ a 120-mm weapon. The goal of this project was to quantify the effects of weapon fire recoil on a simulated human occupant of the MCS.

The U.S. Army Tank-Automotive Research, Development, and Engineering Center’s (TARDEC’s) ride motion simulator (RMS) was used to simulate the effects of gun firing shock on test manikins. The RMS is situated at Tank-Automotive and Armaments Command in Warren, Michigan, and is a reconfigurable six-degree-of-freedom (6-DOF) hexapod motion simulator. It has a dynamic range of movement, has been approved for human use (man rated), and is designed to simulate a wide variety of ground vehicle motions and movements over various terrains and conditions. In this test, the RMS was used to simulate the dynamic motion of two MCS crew positions during weapon firing scenarios: the driver and the gunner. The driver and gunner were investigated because they sit orthogonally to each other and thereby experience substantially different shock impulses during weapon firing. The driver faces forward and the gunner sits perpendicular to the driver.

A Hybrid III instrumented anthropometric test device (ATD) capable of measuring neck force, torque, and head acceleration was placed in the seat of the RMS, and data were recorded from the manikin during the firing scenarios. The raw data for this project were collected by the Motion Base Technologies Team of TARDEC and its contractors. The data were sent to the U.S. Army Research Laboratory’s (ARL’s) Human Research Engineering Directorate for analysis, relative to quantifying potential neck and head injury. Biomechanics researchers at ARL were tasked with relating the neck force, torque, and head accelerations measured by the Hybrid III instrumented manikin to established injury criteria for the neck and head. Data from the Hybrid III manikin were compared to the standards established by the National Highway Traffic Safety Association (NHTSA).

Specifically, the potential for neck injury was estimated on the basis of the N_{ij}, and the potential for head injury was estimated based on the head injury criteria (HIC) (Eppinger et al., 1999; Kleinberger, Sun, Eppinger, Kupper, & Saul, 1998; Eppinger, Sun, Kuppa, & Saul, 2000). The N_{ij} is a measure of the axial and shear loads, as well as the bending moments, imposed on the neck. The “ij” refers to indices for the four injury mechanisms, namely, tension and extension (TE), tension and flexion (TF), compression and extension (CE), compression and flexion (CF) (Kleinberger et al., 1998).

The HIC was first proposed by Versace (1971), but NHTSA modified the measure to be more appropriate for the duration of exposures typical for human tests. HIC is essentially the integral of accelerations over a given time period. In 1986, the appropriate time period was determined to be

36 ms resulting in the HIC_{36} (Kleinberger et al., 1998); however, in 2000, NHTSA proposed a change in the time period to 15 ms, resulting in HIC_{15} (Eppinger et al., 2000). The change from a 36-ms to a 15-ms window occurred because available human tests at the time demonstrated that the probability of injury from longer duration events was low. However, because both the duration and magnitude of the events that are be experienced by occupants of the MCS during weapon firing may be potentially injurious, both the HIC_{15} and the HIC_{36} for each condition are documented in this report.

An alternate standard to apply may be the International Standardization Organization (ISO): 2631-5 (ISO, 2004). Applying this standard to the current data set would not be appropriate, however, for several reasons. First, ISO 2631-5 was written for conditions such as vehicles traveling over rough surfaces, small boats in rough seas, mechanical hammers, etc., when there is a longer duration exposure to whole-body vibration than is experienced by the MCS driver and gunner during weapon firing. Subsequently, it was concluded by biomechanics researchers at ARL that weapon firing will result in more intermittent impulses for the driver and gunner than those for which ISO 2631-5 is designed to be applied. Additionally, ISO 2631-5 assumes the subject is upright and unsupported, which is not the case for the driver and gunner of the MCS. ISO 2531-5 is designed to determine potential for injury to the lumbar spine based on the average daily exposure to whole body vibration and is focused on average daily exposures and predicting lifetime exposure. ISO 2631-5 would be more appropriate for investigating the effects of MCS movement over rough terrain (possibly to an objective rally point or similar), than the effects of weapon firing.

The limitation of using NHTSA standards is that the standards are for a single impulse event (such as a car accident), while the occupants of the MCS will likely be exposed to multiple impulse events (such as the repeated firing of the cannon). Although previous researchers have identified this as a limitation in their work (Hundley & Haley, 1987) and noted the need to establish human tolerance criteria for lower level impact accelerations, an exhaustive literature review did not uncover a standard for multiple events similar to the acceleration experienced by the occupants of the MCS. A standard is needed for multiple events over various time frames, possibly a standard that incorporates parts of ISO2631-5 and the NHTSA standards.

2. Objectives

The objectives of this project were to quantify the effect of turret azimuth and elevation during weapon firing of an MCS on

1. driver N_{ij}, HIC_{15} and HIC_{36},
2. gunner N_{ij}, HIC_{15} and HIC_{36}.

3. Equipment

3.1 Ride Motion Simulator (RMS)

The RMS is a reconfigurable 6-DOF hexapod simulator, which has a dynamic range of movement. It is human rated (meaning live humans can serve as participants within the limitations of the RMS protocol) and can hold a single occupant. The RMS is designed to simulate ground vehicles. Typically, the RMS is used to support Soldier-in-the-loop experiments. However, the high gun fire shocks simulated in this experiment (>2g's) exceeded the current human-rating protocols for the RMS, thus requiring the use of manikins for this study. Before testing, the RMS was tuned by the Motion Base Technologies Team at TARDEC for optimum performance, which ensures that the simulator will react as realistically as possible.

To simulate the interior of the FSC common crew cab, which is used in the MCS, aluminum brackets were mounted in the RMS cab (see figure 1). These brackets replicated the interior of the FCS common crew cab and included potential impact points for the head, arms, and legs. These brackets were designed and mounted, based on computer-aided design drawings of the actual design provided by the United Defense Limited Partnership and General Dynamics Land Systems (GDLS) (Oldaugh, Zywiol, & Stork, 2004).

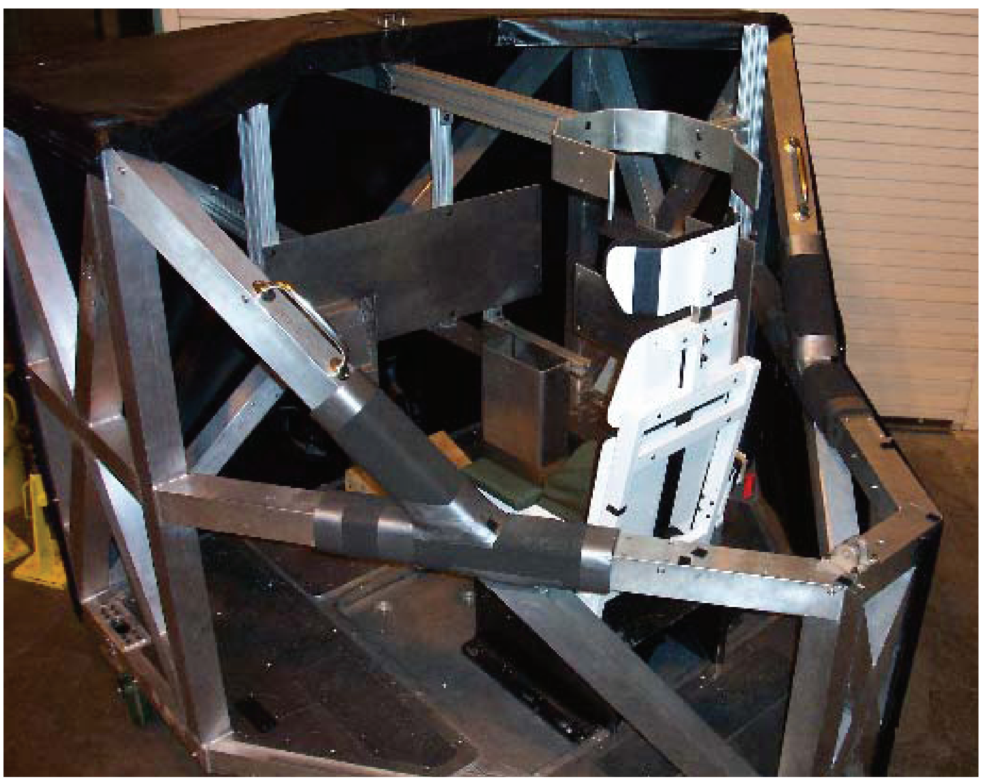

Figure 1. Interior of the RMS, including the aluminum brackets simulating the potential impact points for the head, arms, and legs.

The RMS was set up to simulate stationary vehicle firing. The 6-DOF motions used to simulate weapon firing of the MCS were recorded from a dynamic analysis design system (DADS) simulation, provided by GDLS. In-house software at TARDEC was used to convert the output from the DADS simulation into a form that could be used to control the RMS. More information about this is given in Oldaugh et al. (2004). For both the driver and gunner conditions, the seat was mounted on the floor and oriented in the same direction. In the MCS, the driver and gunner sit orthogonally to each other; the RMS adapted the forces exerted on the seat to simulate the gunner's position without rotating the seat.

3.2 Hybrid III ATD

One of TARDEC's support contractors, Dynamic Research, Inc. (DRI), develops, manufacturers, maintains, and provides rental of specialized crash test dummies for various applications, including injury evaluation and protection system feasibility research. The DRI crash dummies are unique among commercially available motor vehicle crash test dummies in that all data acquisition components, including sensors and power sources, are internal. This is especially important in applications where instrument cables could interfere with or distort dummy motions (as in, for example, unbelted car occupants, pedestrians, motorcyclists, all-terrain vehicles, etc.). In this regard, it is well suited to the study of multiple impacts (Oldaugh, Zywiol, & Stork, 2004).

The specific ATD used for this study was a Hybrid III, 50th percentile male. The ATD weighed 172.3 pounds, was 69 inches tall, and had a sitting height of 34.8 inches (NATSA, 2007). Although referred to as the 50th percentile male, this manikin would be characterized as between the 50th and 55th percentiles for weight, 50th percentile for standing height, and as the 20th percentile for sitting height according to the 1988 U.S. Army Anthropometric Survey (ANSUR) database (Gordon, Churchill, Clauser, Bradtmiller, McConville, Tebbets, & Walker, 1989).

The ATD is instrumented with force transducers and accelerometers capable of providing information about the forces exerted on and acceleration of the head, neck, thorax, and limbs. Specifically for this study, acceleration of the head (all three orthogonal directions) and force and torque about the upper neck are of interest.

4. Experimental Design

4.1 Independent Variables

- Turret azimuth (levels: 0, 45, 90, 135, 180); increasing azimuth indicates a clockwise rotation of the turret.
- Turret elevation (levels: -10, 0, 10, 20, 30),
- Seat position (levels: driver, gunner).

4.2 Dependent Variables

- Head injury criteria, with a 15-ms window (HIC_{15}). See the data analysis for more information about the time windows,
- Head injury criteria with a 36-ms window (HIC_{36}),
- Neck injury criteria (N_{ij}).

4.3 Worst Case Scenario

In addition to the turret azimuth and elevation conditions listed, TARDEC collected data for the "worst case scenario". The worst case scenario condition was defined as azimuth = 150 degrees, and the manikin was restrained with a three-point harness (instead of the five-point harness) in the driver's seat. Additionally, a cupola was present, which was an aluminum bracket around the head that allowed for 3 inches of head movement. The worst case scenario was tested in all the elevation conditions. However, because of confounding effects of adding the cupola (the worst case scenario was the only condition with the cupola), only summary statistics of the worst case scenario are presented, and the worst case scenario data were not compared to the remainder of the data set. Worst case scenario data were only collected for the driver.

4.4 Statistical Analysis

A repeated measures analysis of variance (ANOVA) with within-subject effects of azimuth and elevation was used to determine if statistically significant differences existed between azimuth conditions and elevation conditions and to determine if a significant Azimuth x Elevation interaction was present. Because the focus of the study was on the injury potential for both the driver and the gunner (not focused on which position was potentially more injurious), no statistical comparisons were made between driver and gunner positions. The Statistical Package for the Social Sciences (SPSS)[1] version 14.0.1 was used for all statistical analyses.

5. Procedure

The experimental procedure consisted of a series of repetitive steps. These steps were repeated for each azimuth, elevation and occupant position condition. The procedure that was followed is

1. Set RMS input to simulate specific azimuth and elevation condition.
2. Set the manikin to a seated default position for occupant = driver condition. The manikin was strapped into the seat in the same way a human occupant would be strapped in if the human used all the provided straps correctly.

[1]SPSS is a registered trademark of SPSS, Inc.

3. Bring the RMS to ride level.
4. Begin recording with the manikin data acquisition system.
5. Begin recording simulator response.
6. Run a shock pulse through the RMS.
7. Stop data acquisition system.
8. Stop the test briefly to reset the manikin position if needed. The manikin needed to be repositioned if it was no longer in the original default position.
9. Repeat steps 2 through 9 until three trials of data were collected for a given azimuth and elevation condition.
10. Download data from the manikin.
11. Repeat steps 1 through 11 for each azimuth and elevation condition.
12. Repeat steps 1 through 12 for occupant = gunner condition.

Data were sampled from the manikin at 10,000 Hz and were filtered with a sixth order low pass Butterworth filter at 2500 Hz. The data ARL received had already been filtered and scaled appropriately and were in the units of *g* (gravity) for accelerations, *Nm* (newton*meters) for torque, and *kN* (kilo-newtons) for force.

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6. Data Analysis

6.1 N_{ij} Calculation

N_{ij} was calculated according to NHTSA guidelines (Kleinberger et al., 1998; Eppinger et al., 1999; Eppinger et al., 2000). Equation 1 was used to calculate N_{ij}.

$$N_{ij} = \frac{F_z}{F_{\text{int}}} + \frac{M_y}{M_{\text{int}}} \tag{1}$$

in which F_z is the axial load, F_{int} is the critical intercept value of load used for normalization, M_y is the flexion/extension moment, and M_{int} is the critical intercept value for moment used for normalization. F_z and M_y are recorded from the manikin. F_{int} and M_{int} are pre-determined values specific to the size ATD used for the study. Because this study used a Hybrid III 50th percentile male ATD, F_{int} was set to 3600 N for tension and compression, and M_{int} was set to 410 Nm for flexion and 125 Nm for extension (Kleinberger et al., 1998; Eppinger et al., 1999; Eppinger et al., 2000).

The maximum of the absolute value of the N_{ij} (equation 2) was calculated and is reported.

$$N_{ij} = \max(abs(N_{ij})) \tag{2}$$

NHTSA recommends an injury criteria for N_{ij} of 1.0, meaning that test results of greater than 1.0 pose a significant injury risk, while test results of less than 1.0 are considered acceptable for a single impulse event. In addition to the injury criteria, the N_{ij} can be used to calculate the probability of several different types of injuries. Table 1 summarizes the equation used to estimate the potential for each injury severity level (Eppinger et al., 1999).

Table 1. Equations used to calculate probability of injury, based on N_{ij}.

Severity of Injury	Equation
Moderate or greater	$p = \frac{1}{1+e^{2.054-1.195N_{ij}}}$
Serious or greater	$p = \frac{1}{1+e^{3.227-1.969N_{ij}}}$
Severe or greater	$p = \frac{1}{1+e^{2.693-1.195N_{ij}}}$
Critical or greater	$p = \frac{1}{1+e^{3.817-1.195N_{ij}}}$

6.2 HIC Calculation

HIC was calculated according to NHTSA guidelines with two different time windows: 15 ms and 36 ms. These time windows were chosen because they are the ones recommended by NHTSA (Kleinberger et al., 1998; Eppinger et al., 1999; Eppinger et al., 2000). HIC was calculated by equation 3:

$$HIC = \max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}(t_2 - t_1) \tag{3}$$

in which t_1 and t_2 represent any two points in time (determined by the time window) during the acceleration impulse, and $a(t)$ represents the resultant acceleration of the head at a specific point in time (units for acceleration are *g*). Subsequently, to calculate HIC_{15}, t_2 - t_1 was set to 0.015 second and to calculate HIC_{36}, t_2 - t_1 was set to 0.036 second; *dt* was 0.0001 for all analyses. The units for time are seconds.

NHTSA recommends an injury criterion for HIC_{15} of 700 and for HIC_{36} of 1000. This criterion indicates that test results of greater than 700 for HIC_{15} or 1000 for HIC_{36} pose a significant injury risk, while test results of less than the criterion are considered acceptable for a single impulse. In addition to the injury criteria, the HIC can be used to calculate the probability of moderate head injuries via equation 4.

$$p = N\left(\frac{\ln(HIC) - \mu}{\sigma}\right) \tag{4}$$

in which N represents the cumulative normal distribution, μ = 6.96352, and σ = 0.84664 (Eppinger et al., 1999).

7. Results

7.1 Driver

There was a significant main effect of azimuth (F = 94.282, *p* = 0.000) and elevation (F = 97.137, *p* = 0.000) and a significant Azimuth x Elevation interaction (F = 9.054, *p* = 0.000) on HIC_{15} for the driver. Similarly, there was a significant main effect of azimuth (F = 148.084, *p* = 0.000) and elevation (F = 83.549, *p* = 0.000) and a significant Azimuth x Elevation interaction (F = 12.577, *p* = 0.000) on HIC_{36} for the driver. Additionally, there was a significant main effect of azimuth (F = 2204.569, *p* = 0.000) and elevation (F = 274.356, *p* = 0.000) and a significant Azimuth x Elevation interaction (F = 89.988, *p* = 0.000) on the N_{ij} (see table 2) for the driver.

Table 2. F-ratios and *p*-values for statistics on driver configuration.

	HIC_15	**HIC_36**	**Nij**
Az (p-value)	0.000	0.000	0.000
Az (F-Ratio)	94.282	148.084	2204.569
El (p-value)	0.000	0.000	0.000
El (F-Ratio)	97.137	83.549	274.356
Az*El (p-value)	0.000	0.000	0.000
Az*El (F-Ratio)	9.054	12.577	89.988

Pairwise comparisons were performed to determine which azimuth and elevation conditions were statistically different from each other (see table 3). Pairwise comparisons revealed statistically significant differences between all azimuth conditions excluding the 45 and 135 degrees of azimuth conditions for HIC_{15} and between all elevation conditions for HIC_{15}. Additionally, pairwise comparisons revealed statistically significant differences between all azimuth conditions excluding the 0 and 135 degrees of azimuth and between the 45 and 135 degrees of azimuth conditions for HIC_{36} and between all elevation conditions excluding the -10 and 0 degrees of elevation conditions for HIC_{36}. Pairwise comparisons also showed statistically significant differences between all azimuth conditions for N_{ij}. Pairwise comparisons showed statistically significant differences between all elevation conditions for N_{ij} except the 0 and 10 degrees of elevation conditions, the 0 and 20 degrees of elevation conditions, and between the 10 and 20 degrees of elevation conditions.

Means (and standard error of the mean [SEM]) for each azimuth and elevation condition for HIC_{15} are summarized in table 4 and shown in figure 2.

Table 3. *p*-values for pairwise comparisons: driver.

Azimuth Conditions		HIC_{15}	HIC_{36}	N_{ij}
0	45	0.000	0.000	0.000
0	90	0.000	0.000	0.000
0	135	0.000	0.047	0.000
0	180	0.000	0.000	0.000
45	90	0.000	0.000	0.000
45	135	0.090	0.556	0.000
45	180	0.000	0.000	0.000
90	135	0.000	0.000	0.000
90	180	0.000	0.000	0.000
135	180	0.000	0.000	0.000
Elevation Conditions		**HIC_{15}**	**HIC_{36}**	**N_{ij}**
-10	0	0.002	0.467	0.000
-10	10	0.000	0.001	0.000
-10	20	0.000	0.000	0.000
-10	30	0.000	0.000	0.000
0	10	0.012	0.006	0.104
0	20	0.000	0.000	0.129
0	30	0.000	0.000	0.000
10	20	0.000	0.000	0.910
10	30	0.000	0.000	0.000
20	30	0.000	0.000	0.000

Table 4. Means (SEM) for driver: HIC_{15}.

		Azimuth Condition				
		0	**45**	**90**	**135**	**180**
Elevation	**-10**	0.268 (0.008)	0.291 (0.008)	0.353 (0.011)	0.242 (0.015)	0.200 (0.003)
	0	0.246 (0.013)	0.215 (0.026)	0.321 (0.012)	0.272 (0.006)	0.193 (0.005)
	10	0.259 (0.013)	0.171 (0.012)	0.306 (0.001)	0.231 (0.006)	0.195 (0.006)
	20	0.263 (0.004)	0.174 (0.002)	0.251 (0.017)	0.187 (0.007)	0.136 (0.007)
	30	0.230 (0.009)	0.153 (0.002)	0.163 (0.010)	0.128 (0.004)	0.091 (0.002)

Means (and standard error of the means) for each azimuth and elevation condition for HIC_{36} are summarized in table 5 and shown in figure 3.

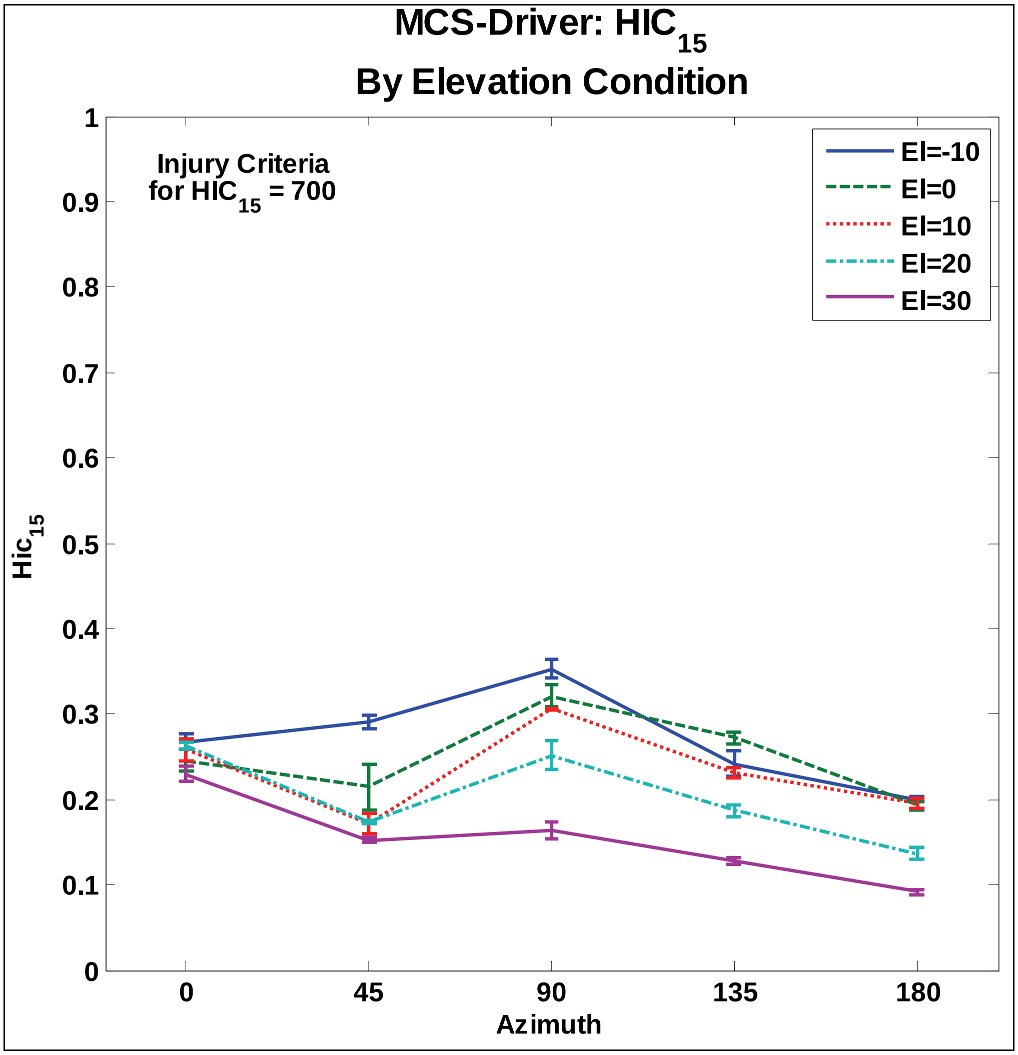

Figure 2. MCS driver HIC_{15} by elevation.

Table 5. Means (SEM) for driver: HIC_{15}.

		Azimuth Condition				
		0	**45**	**90**	**135**	**180**
Elevation	**-10**	0.478 (0.004)	0.503 (0.013)	0.819 (0.021)	0.560 (0.035)	0.413 (0.007)
	0	0.492 (0.020)	0.488 (0.061)	0.745 (0.028)	0.619 (0.016)	0.379 (0.014)
	10	0.526 (0.007)	0.387 (0.029)	0.705 (0.006)	0.537 (0.013)	0.374 (0.010)
	20	0.579 (0.011)	0.392 (0.006)	0.579 (0.034)	0.427 (0.016)	0.295 (0.013)
	30	0.503 (0.015)	0.341 (0.004)	0.382 (0.024)	0.298 (0.008)	0.180 (0.003)

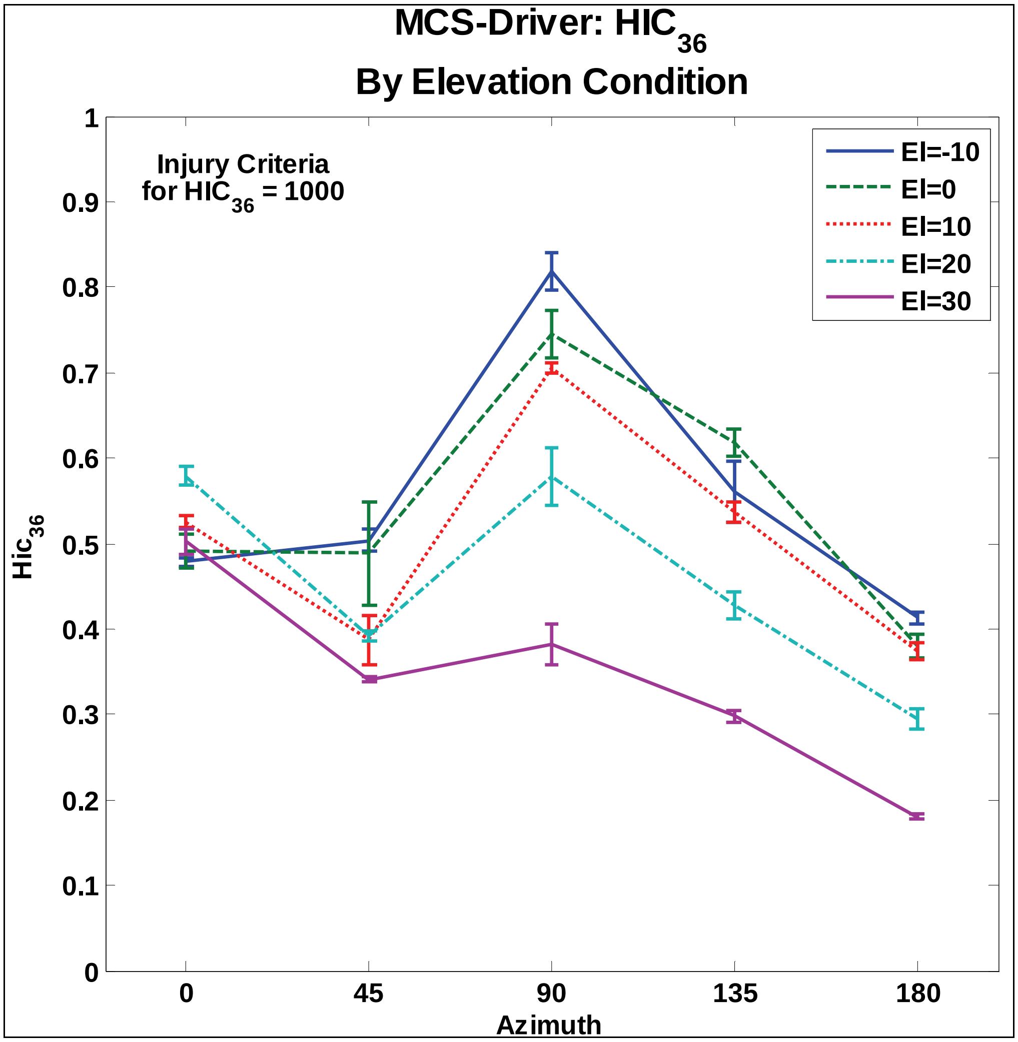

Figure 3. MCS driver HIC_{36} by elevation.

Additionally, sample resultant head acceleration, HIC_{15} and HIC_{36} time series data from the azimuth = 0, elevation = 0 condition are presented in figure 4. Similar data for the azimuth = 0, elevation = 30 condition are presented in figure 5; data for the azimuth = 180, elevation = 0 condition are presented in figure 6. As shown in each of the figures, both the HIC_{15} and the HIC_{36} are well below the injury criteria of 700 and 1000, respectively.

Means (and standard error of the means) for each azimuth and elevation condition for N_{ij} are summarized in table 6 and shown in figure 7.

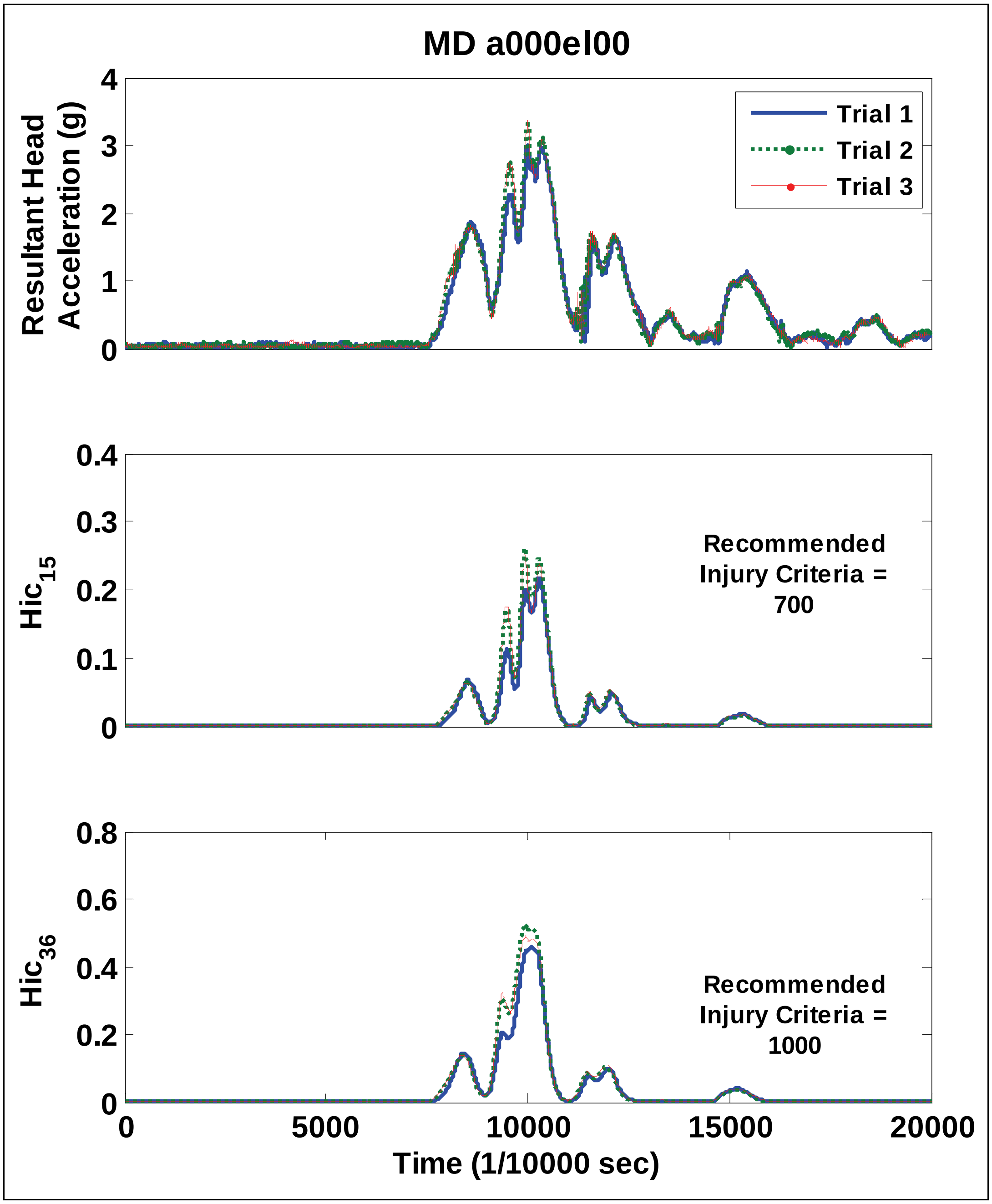

Figure 4. Sample time series data for driver in the azimuth = 0 and elevation = 0 conditions.

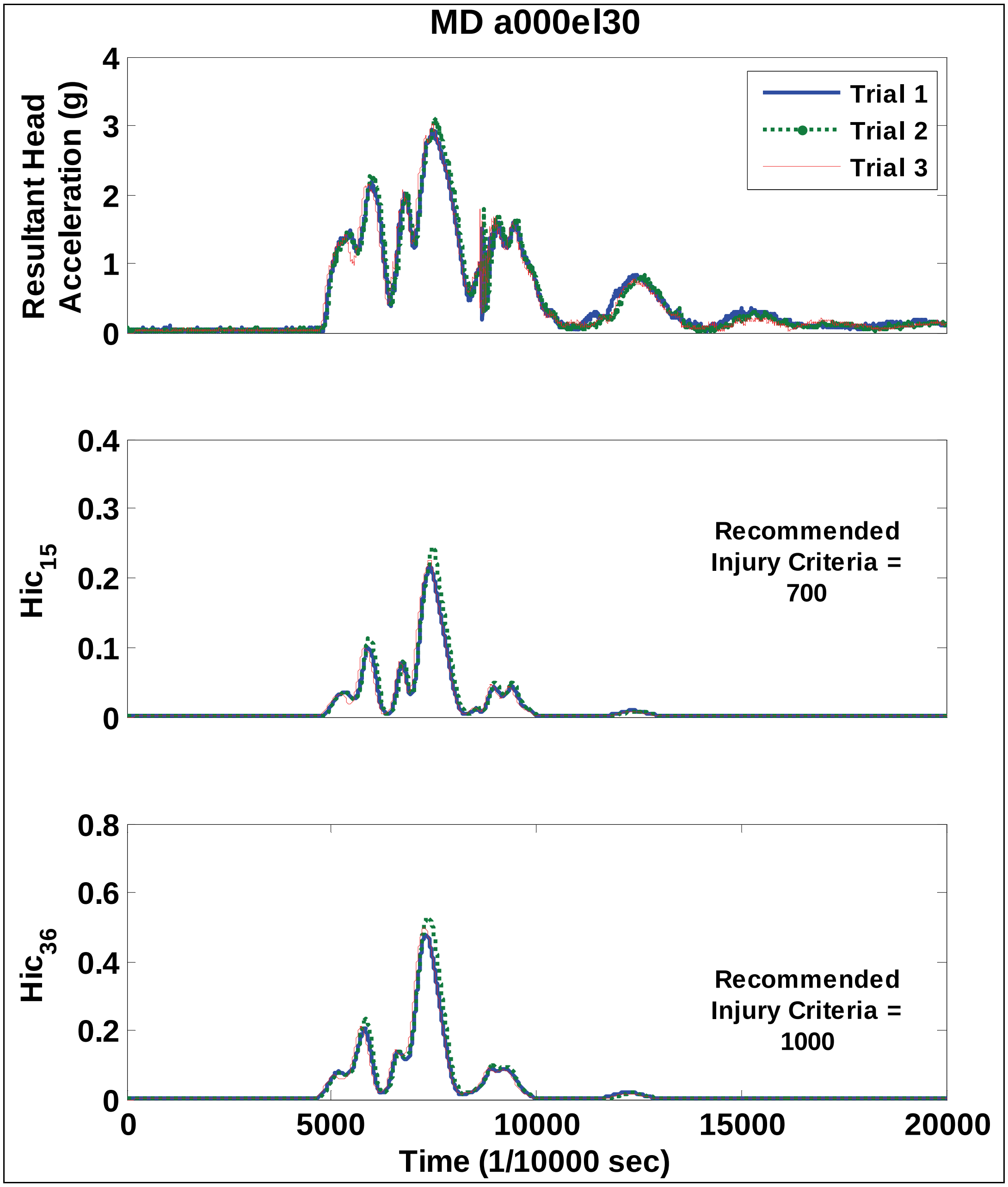

Figure 5. Sample time series data for driver in the azimuth = 0 and elevation = 30 conditions.

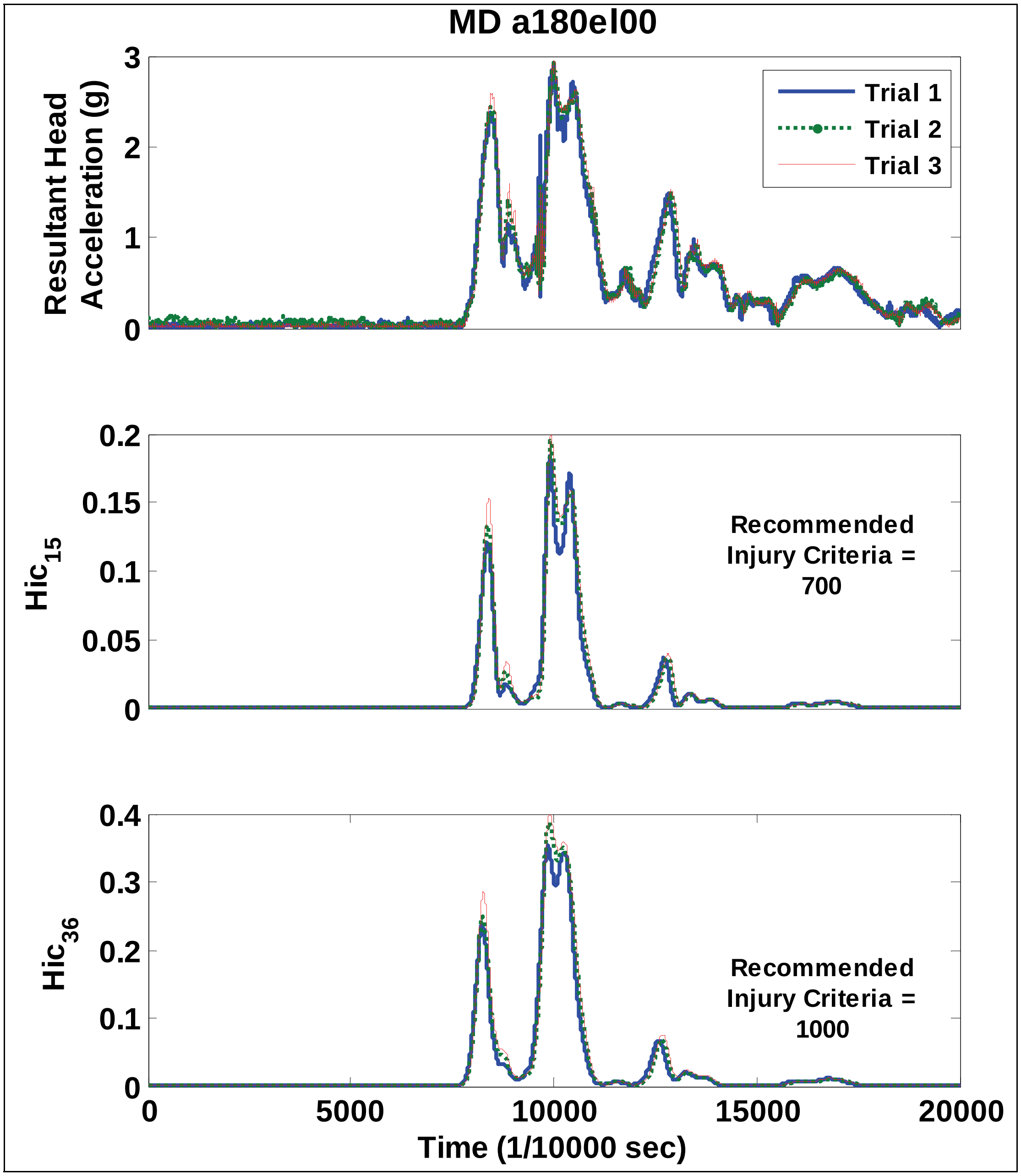

Figure 6. Sample time series data for driver in the azimuth = 0 and elevation = 30 conditions.

Table 6. Means (SEM) for driver: N_{ij}.

		Azimuth Condition				
		0	**45**	**90**	**135**	**180**
Elevation	**-10**	0.143 (0.002)	0.151 (0.001)	0.028 (0.001)	0.051 (0.001)	0.114 (0.004)
	0	0.118 (0.005)	0.048 (0.004)	0.025 (0.001)	0.057 (0.000)	0.105 (0.002)
	10	0.120 (0.001)	0.053 (0.004)	0.024 (0.000)	0.052 (0.001)	0.095 (0.001)
	20	0.112 (0.002)	0.070 (0.000)	0.020 (0.001)	0.041 (0.000)	0.102 (0.001)
	30	0.102 (0.000)	0.066 (0.001)	0.015 (0.001)	0.036 (0.001)	0.080 (0.000)

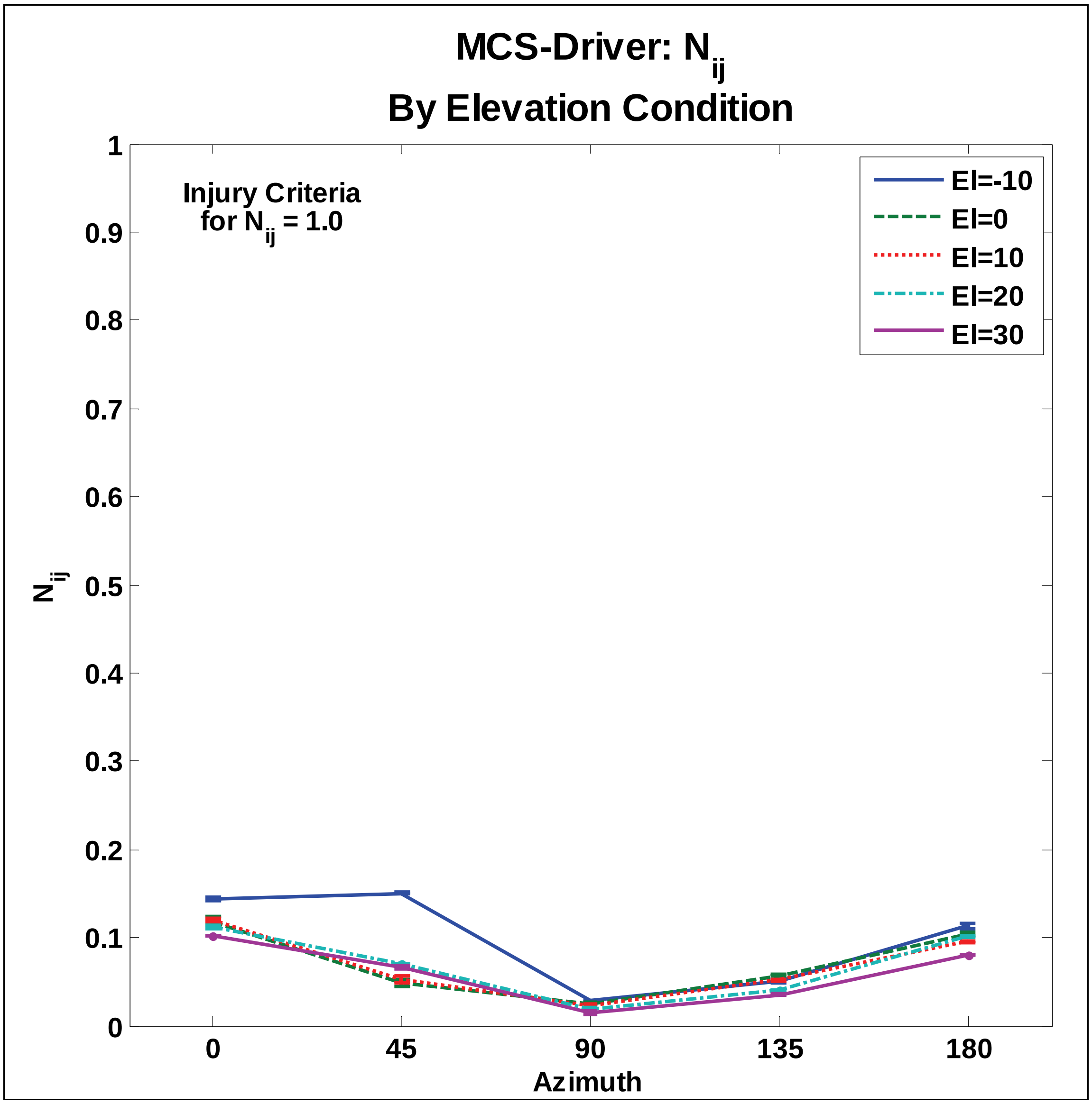

Figure 7. MCS-driver N_{ij} by elevation.

Sample time series data for the N_{ij} and the standard N_{ij} plot are presented for the driver azimuth = 0, elevation = 0 conditions (figure 8), the driver azimuth = 0, elevation = 30 condition (figure 9) and the driver azimuth = 180, elevation = 0 conditions (figure 10). As noted in the figures, the N_{ij} is less than the injury threshold throughout the entire trial.

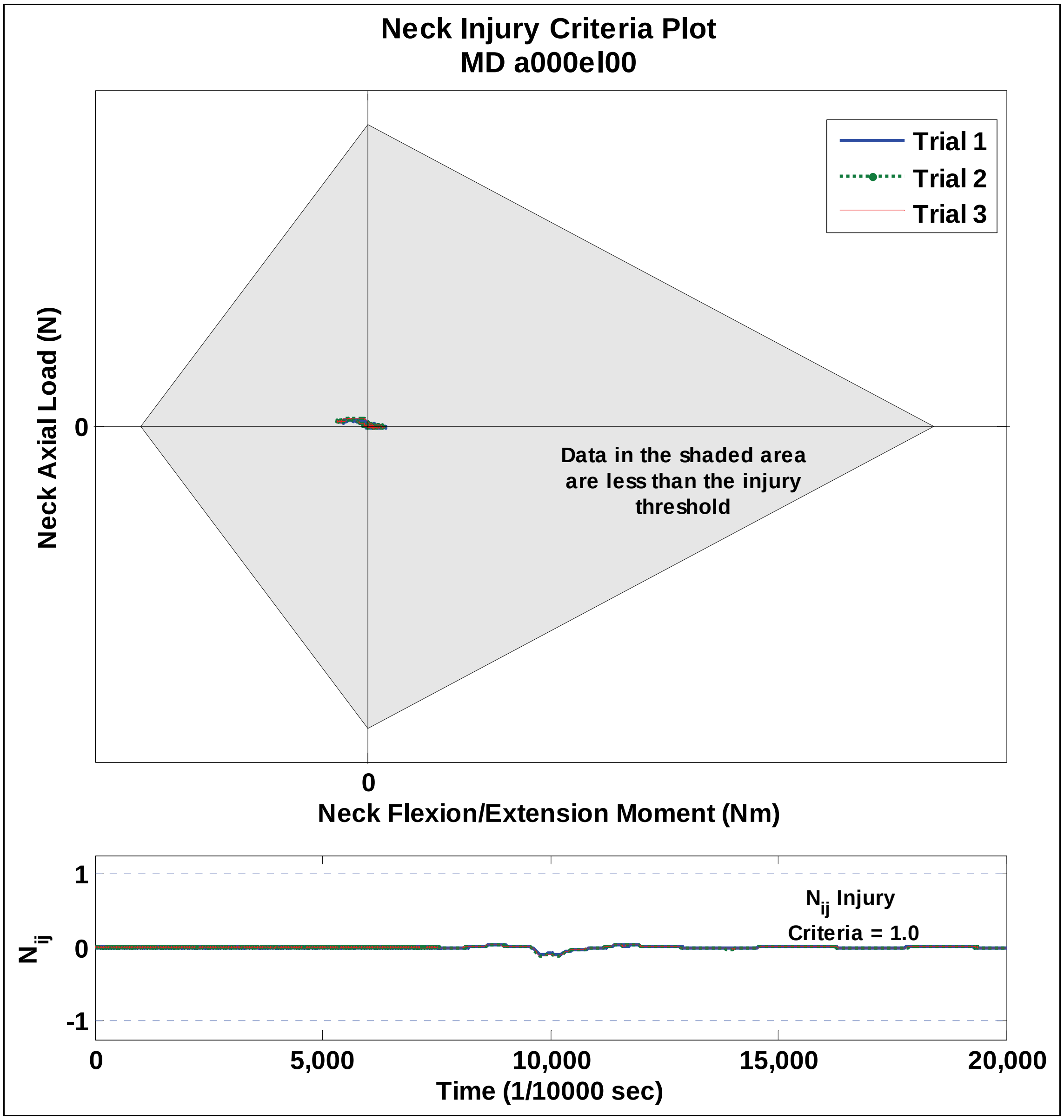

Figure 8. N_{ij} plot for driver, azimuth = 0, elevation = 0.

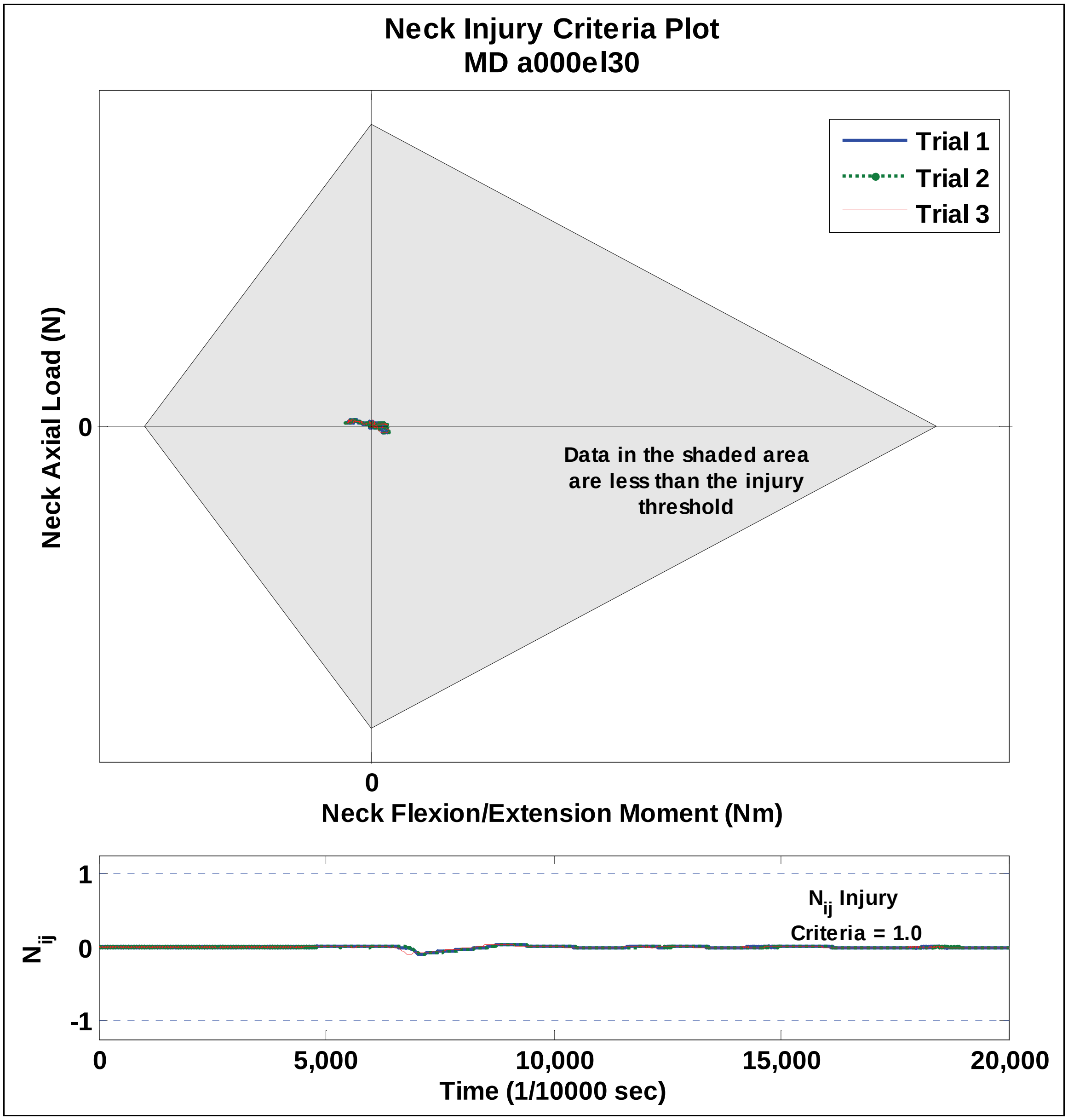

Figure 9. N_{ij} plot for driver, azimuth = 0, elevation = 30.

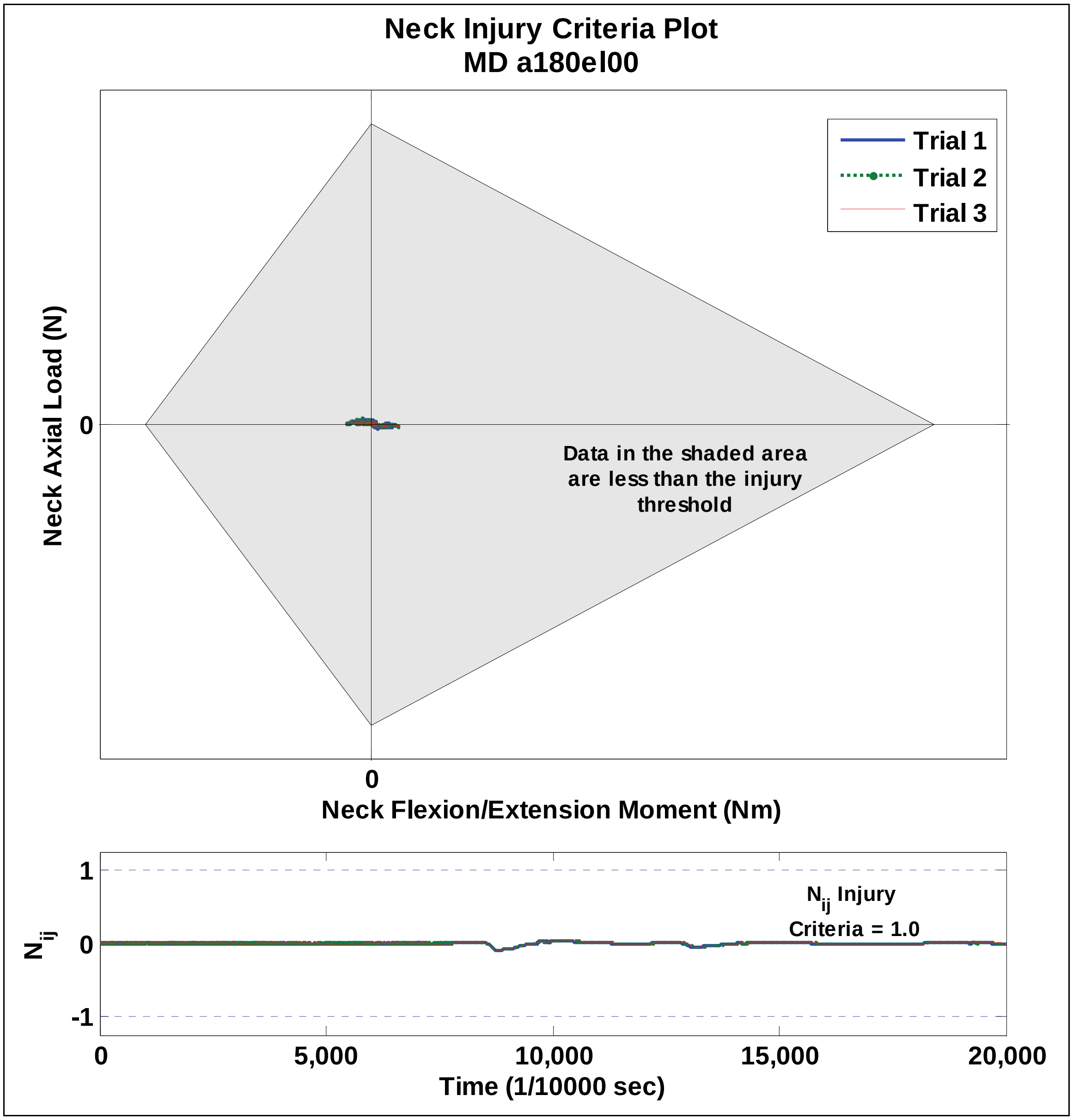

Figure 10. N_{ij} plot for driver, azimuth =180, elevation = 0.

7.2 Gunner

There was a significant main effect of azimuth (F = 258.962, $p = 0.000$) and elevation (F = 331.716, $p = 0.000$) and a significant Azimuth x Elevation interaction (F = 20.488, $p = 0.000$) on HIC_{15} for the gunner. Similarly, was a significant main effect of azimuth (F = 230.217, $p = 0.000$) and elevation (F = 338.986, $p = 0.000$) and a significant Azimuth x Elevation interaction (F = 19.131, $p = 0.000$) on HIC_{36} for the gunner. Additionally, there was a significant main effect of azimuth (F = 121.788, $p = 0.000$) and elevation (F = 9.456, $p = 0.000$) and a significant Azimuth x Elevation interaction (F = 2.330, $p < 0.012$) on the N_{ij} (see table 7) for the gunner.

Table 7. F-ratios and *p*-values for statistics on gunner configuration.

	HIC_15	HIC_36	Nij
Az (p-value)	0.000	0.000	0.000
Az (F-Ratio)	258.962	230.217	121.788
El (p-value)	0.000	0.000	0.000
El (F-Ratio)	331.716	338.986	9.456
Az*El (p-value)	0.000	0.000	0.012
Az*El (F-Ratio)	20.488	19.131	2.330

Pairwise comparisons were performed to determine which azimuth and elevation conditions were statistically different from each other (see table 8). Statistically significant differences were found between all pairs of azimuth conditions except between the 45 and 90 degrees of azimuth condition for the HIC_{15} and HIC_{36}. Additionally, statistically significant differences were found between all pairs of azimuth conditions except the 0 and 180 degrees of azimuth condition for the N_{ij}. Pairwise comparisons revealed statistically significant differences between all elevation conditions except the -10 and 0 degrees of elevation for the HIC_{15} and HIC_{36}. Pairwise comparisons also showed statistically significant differences between all elevation conditions except between the -10 and 0, 10, and 20 degrees of elevation conditions, between the 0 and 10 degrees of elevation condition, and between the 20 and 30 degrees of elevation condition.

Table 8. *p*-values for pairwise comparisons: gunner.

Azimuth Conditions		HIC_{15}	HIC_{36}	N_{ij}
0	45	0.000	0.000	0.000
0	90	0.000	0.000	0.000
0	135	0.008	0.086	0.000
0	180	0.000	0.000	0.703
45	90	0.337	0.315	0.000
45	135	0.000	0.000	0.018
45	180	0.000	0.000	0.000
90	135	0.000	0.000	0.000
90	180	0.000	0.000	0.000
135	180	0.000	0.000	0.000
Elevation Conditions		**HIC_{15}**	**HIC_{36}**	**N_{ij}**
-10	0	0.115	0.403	0.840
-10	10	0.049	0.009	0.058
-10	20	0.000	0.000	0.076
-10	30	0.000	0.000	0.000
0	10	0.001	0.001	0.088
0	20	0.000	0.000	0.049
0	30	0.000	0.000	0.000
10	20	0.000	0.000	0.000
10	30	0.000	0.000	0.000
20	30	0.000	0.000	0.057

Means (and standard error of the mean) for each azimuth and elevation condition for HIC_{15} are summarized in table 9 and shown in figure 11.

Table 9. Means (SEM) for gunner: $HIC_{15.}$

		Azimuth Condition				
		0	**45**	**90**	**135**	**180**
Elevation	**-10**	0.241 (0.004)	0.273 (0.007)	0.285 (0.006)	0.225 (0.010)	0.106 (0.004)
	0	0.195 (0.010)	0.295 (0.006)	0.306 (0.004)	0.241 (0.005)	0.129 (0.003)
	10	0.166 (0.010)	0.258 (0.007)	0.284 (0.010)	0.241 (0.009)	0.138 (0.009)
	20	0.167 (0.018)	0.139 (0.002)	0.165 (0.003)	0.133 (0.002)	0.102 (0.003)
	30	0.112 (0.005)	0.163 (0.005)	0.110 (0.003)	0.103 (0.003)	0.054 (0.004)

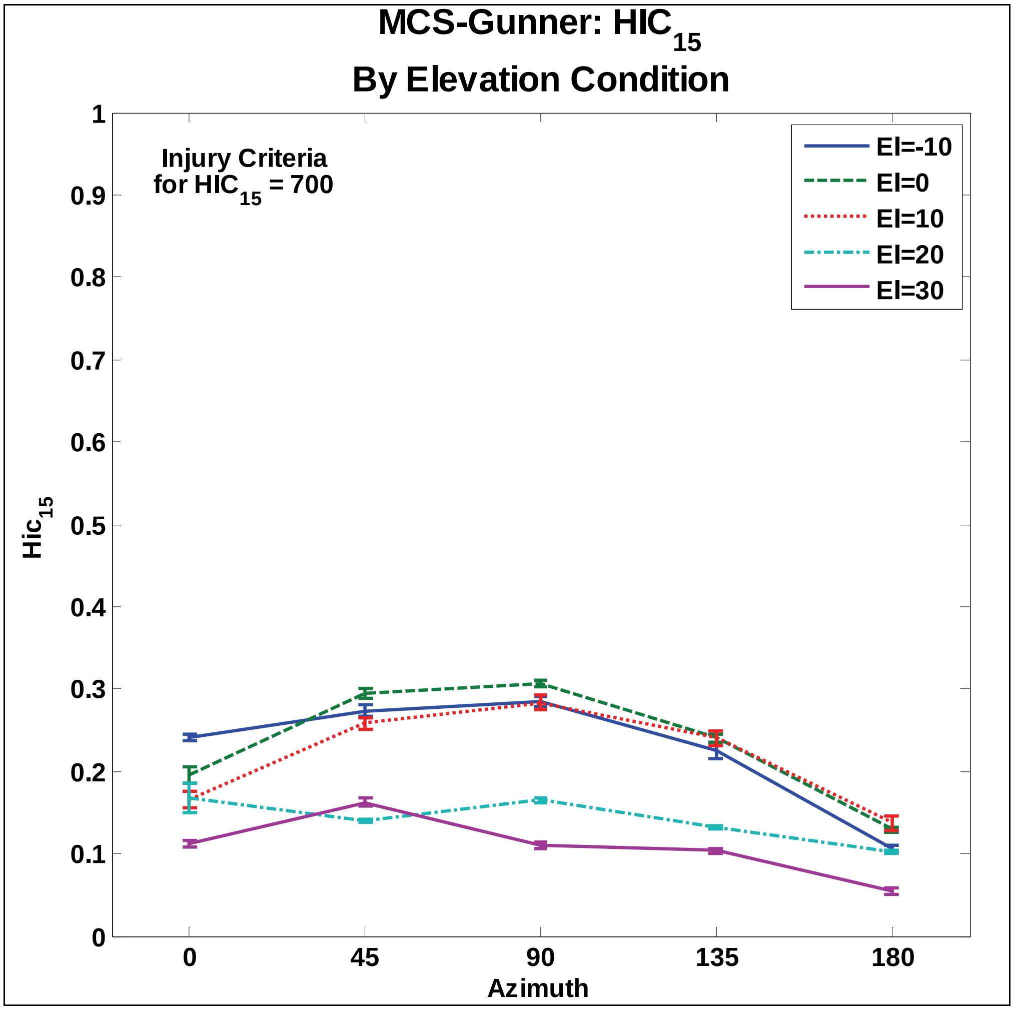

Figure 11. MCS gunner HIC_{15} by elevation.

Means (and standard error of the mean) for each azimuth and elevation condition for HIC_{36} are summarized in table 10 and shown in figure 12.

Table 10. Means (SEM) for gunner: HIC_{36}.

		Azimuth Condition				
		0	**45**	**90**	**135**	**180**
Elevation	**-10**	0.550 (0.009)	0.591 (0.009)	0.594 (0.010)	0.477 (0.016)	0.247 (0.008)
	0	0.450 (0.023)	0.634 (0.009)	0.629 (0.006)	0.493 (0.007)	0.294 (0.007)
	10	0.382 (0.022)	0.549 (0.015)	0.595 (0.016)	0.496 (0.014)	0.310 (0.023)
	20	0.386 (0.043)	0.302 (0.005)	0.341 (0.005)	0.285 (0.001)	0.229 (0.005)
	30	0.257 (0.011)	0.366 (0.011)	0.236 (0.012)	0.192 (0.004)	0.116 (0.009)

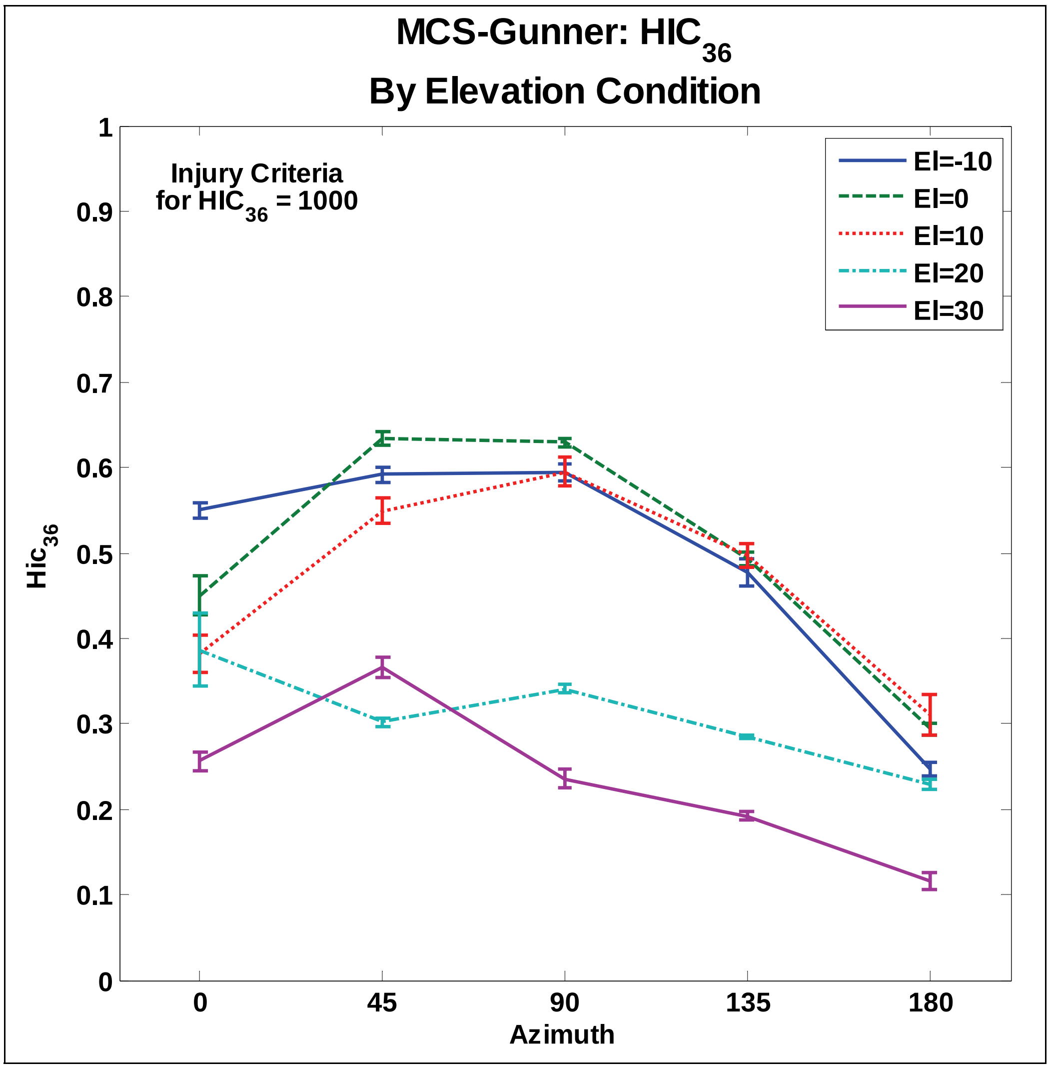

Figure 12. MCS gunner HIC_{36} by elevation.

Additionally, sample resultant head acceleration, HIC_{15} and HIC_{36} time series data from the azimuth = 0, elevation = 0 condition are presented in figure 13. Similar data for the azimuth = 0, elevation = 30 condition are presented in figure 14. Data for the azimuth = 180, elevation = 0 condition are presented in figure 15. As shown in each of the figures, both the HIC_{15} and the HIC_{36} are below the injury criteria.

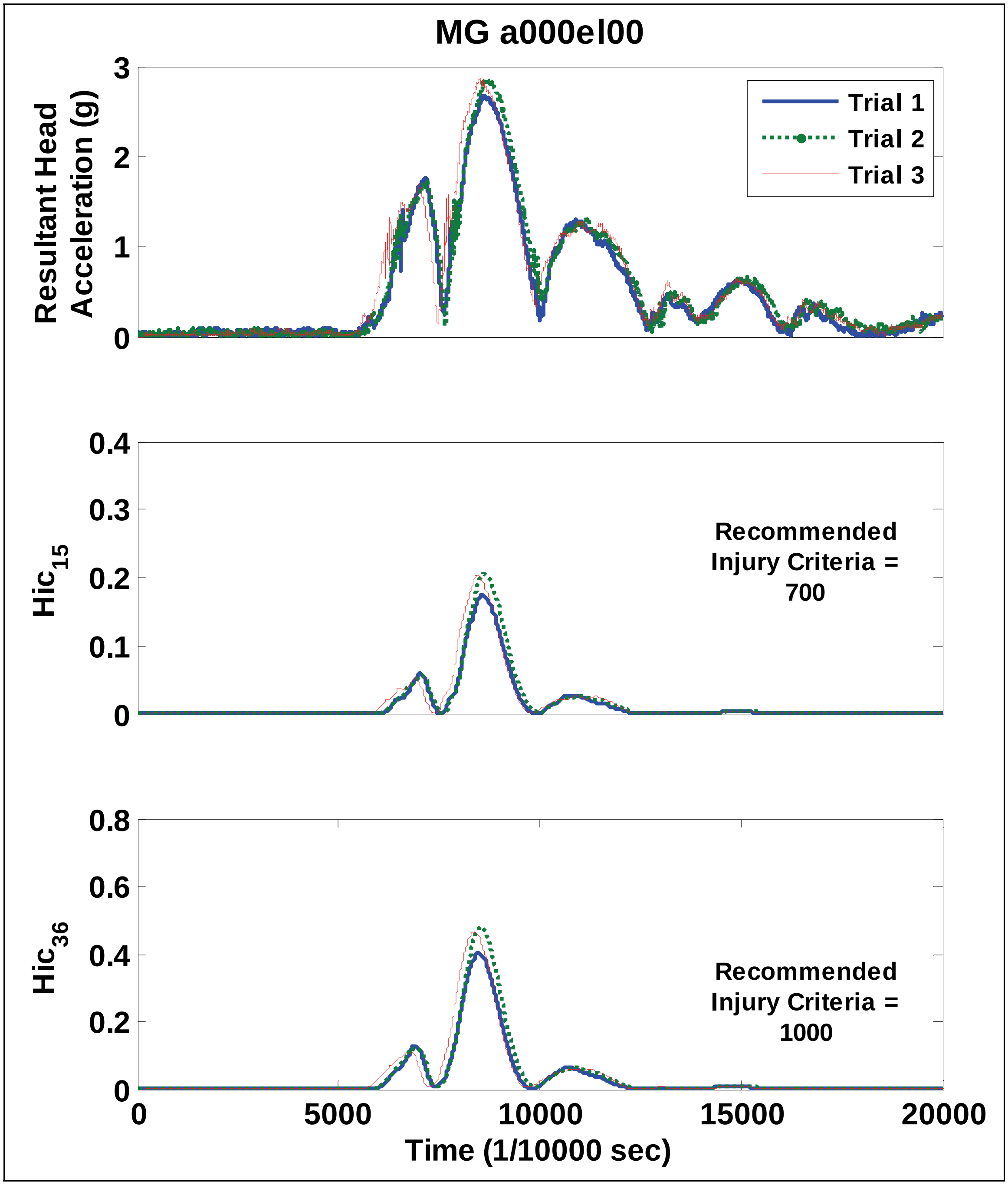

Figure 13. Sample time series data for gunner azimuth = 0, elevation = 0 condition.

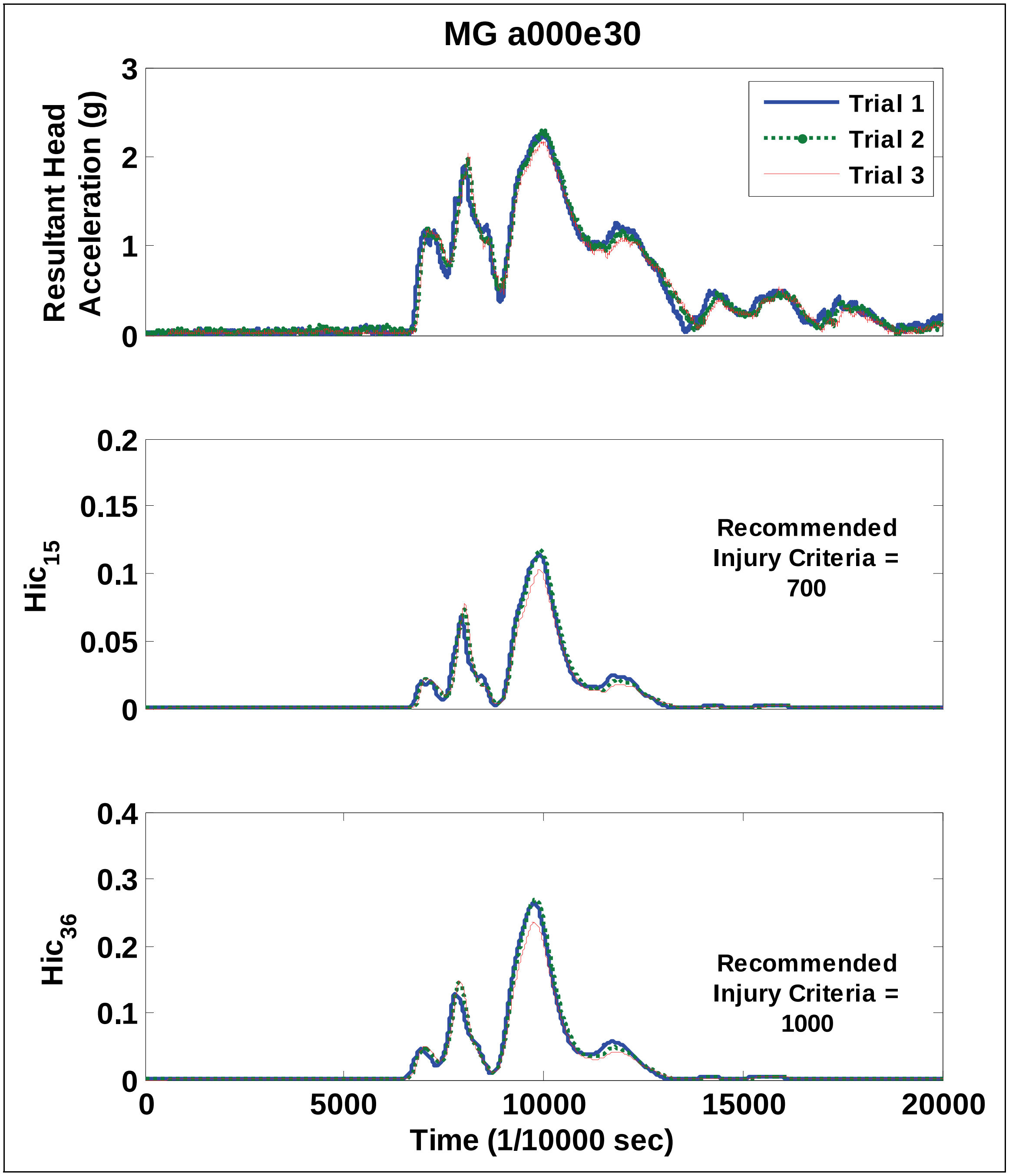

Figure 14. Sample time series data for gunner azimuth = 0, elevation = 30 conditions.

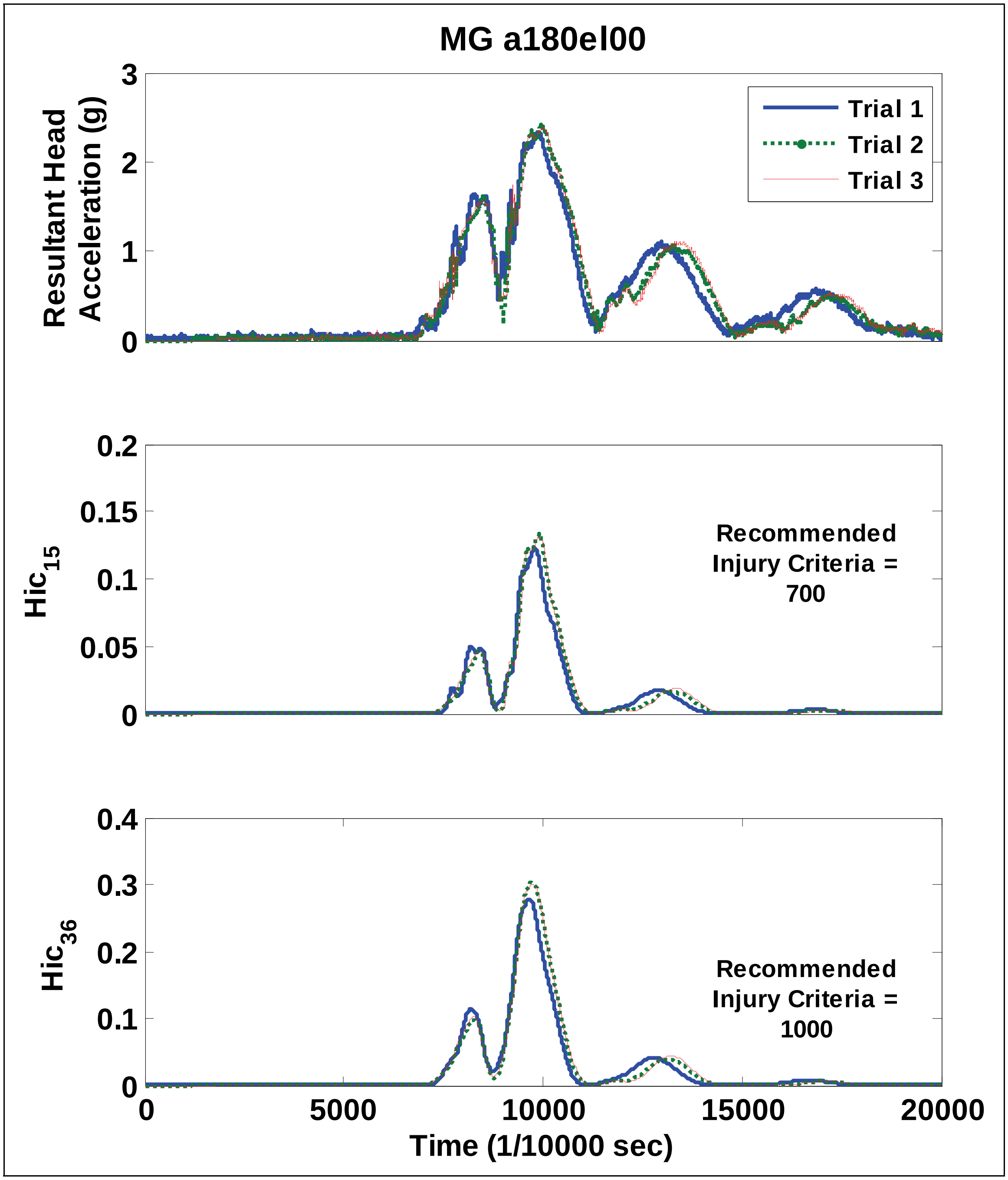

Figure 15. Sample time series data for gunner azimuth = 180, elevation = 0 condition.

Means (and standard error of the means) for each azimuth and elevation condition for N_{ij} are summarized in table 11 and shown in figure 16.

Table 11. Means (SEM) for gunner: N_{ij}.

		Azimuth Condition				
		0	45	90	135	180
Elevation	-10	0.017 (0.000)	0.101 (0.001)	0.129 (0.001)	0.096 (0.001)	0.021 (0.001)
	0	0.013 (0.001)	0.100 (0.001)	0.131 (0.002)	0.106 (0.001)	0.020 (0.002)
	10	0.019 (0.001)	0.095 (0.001)	0.177 (0.049)	0.110 (0.001)	0.023 (0.001)
	20	0.017 (0.002)	0.072 (0.002)	0.108 (0.002)	0.093 (0.002)	0.017 (0.001)
	30	0.017 (0.001)	0.045 (0.001)	0.086 (0.001)	0.083 (0.000)	0.014 (0.000)

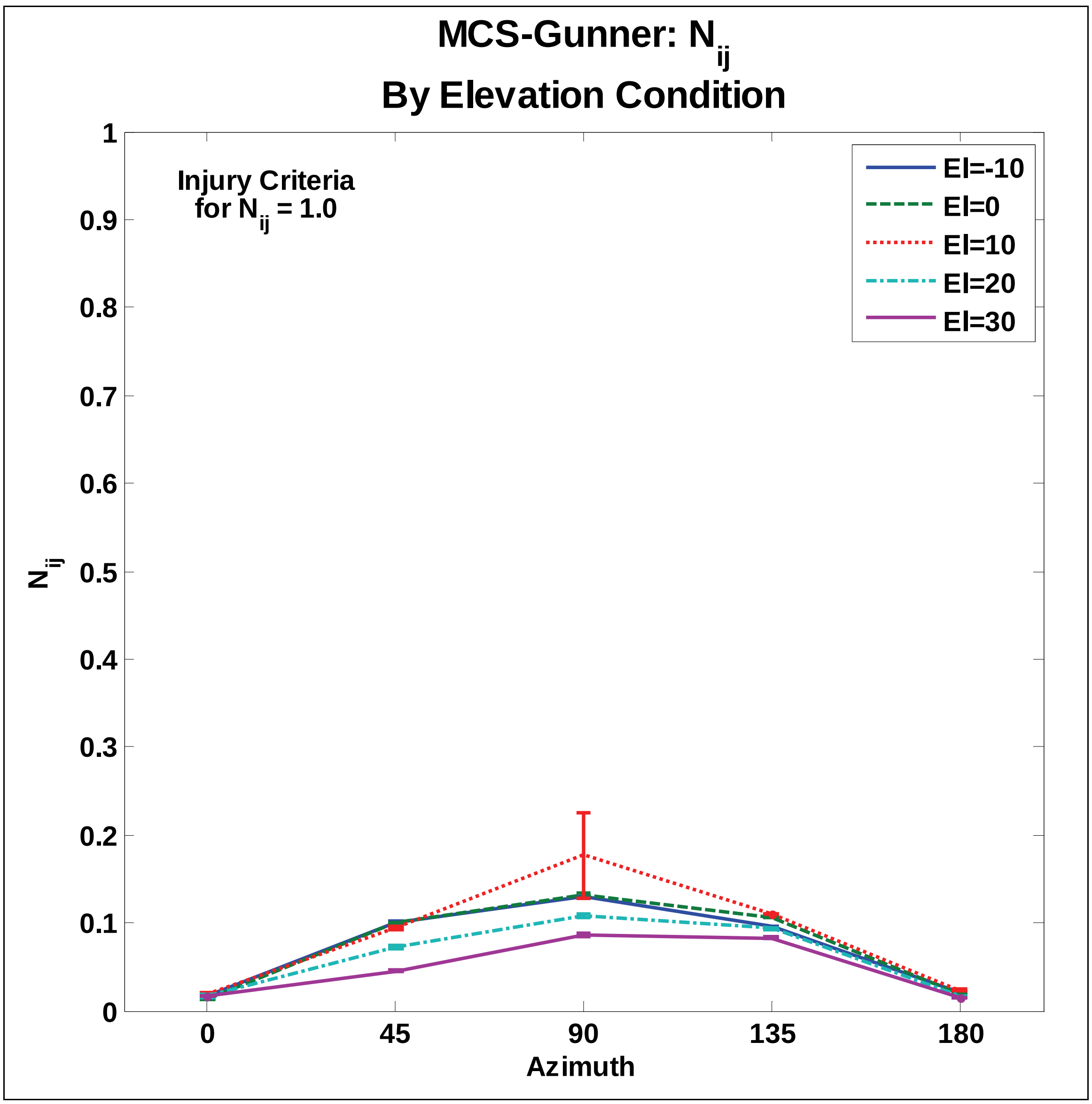

Figure 16. MCS gunner N_{ij} by elevation.

Sample time series data for the N_{ij} and the standard N_{ij} plot are presented for the gunner azimuth = 0, elevation = 0 conditions (figure 17), the gunner azimuth = 0, elevation = 30 condition (figure 18) and the gunner azimuth = 180, elevation = 0 conditions (figure 19). As noted in the figures, the N_{ij} is less than the injury threshold throughout the entire trial.

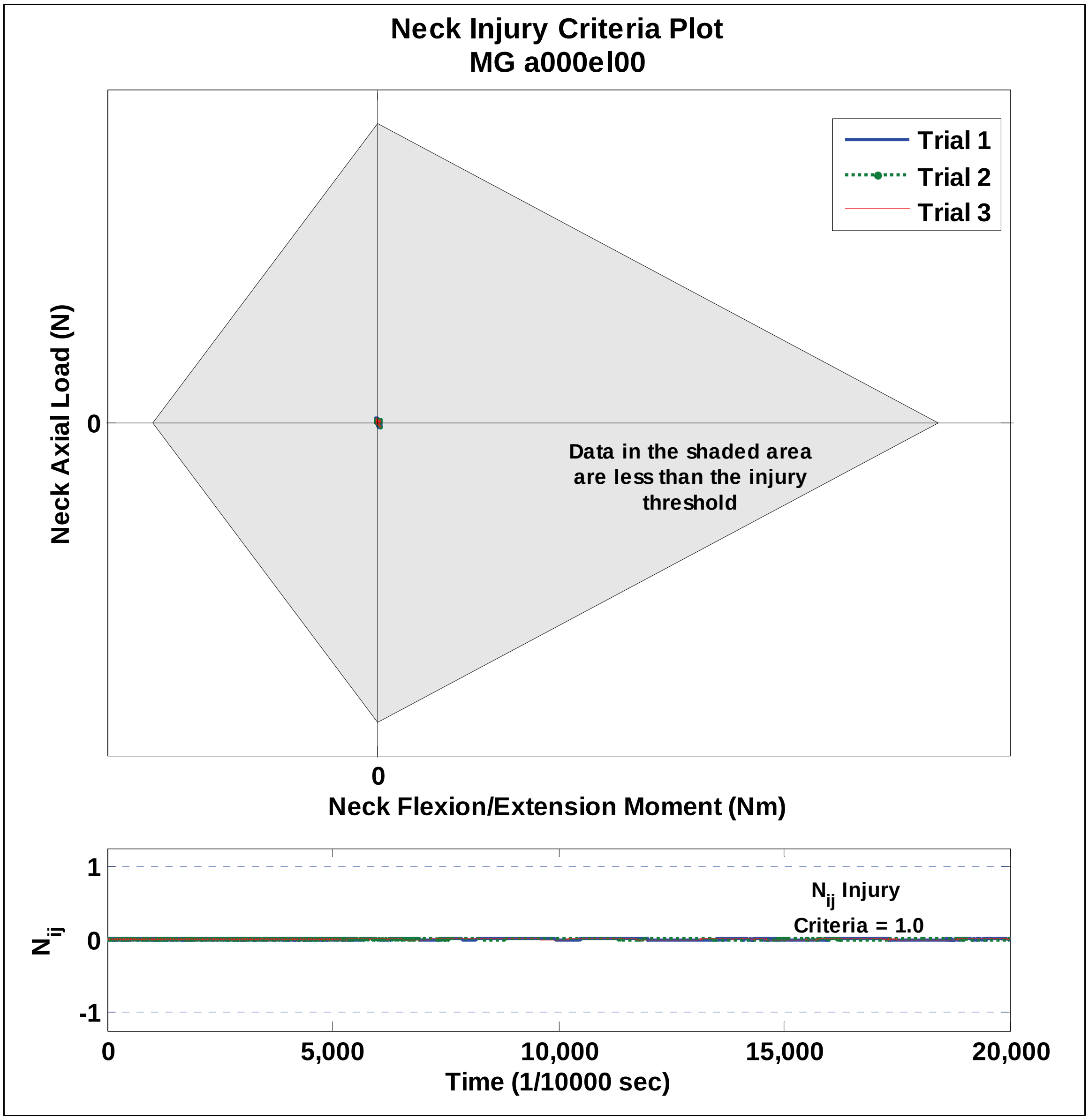

Figure 17. N_{ij} plot for gunner, azimuth = 0, elevation = 0.

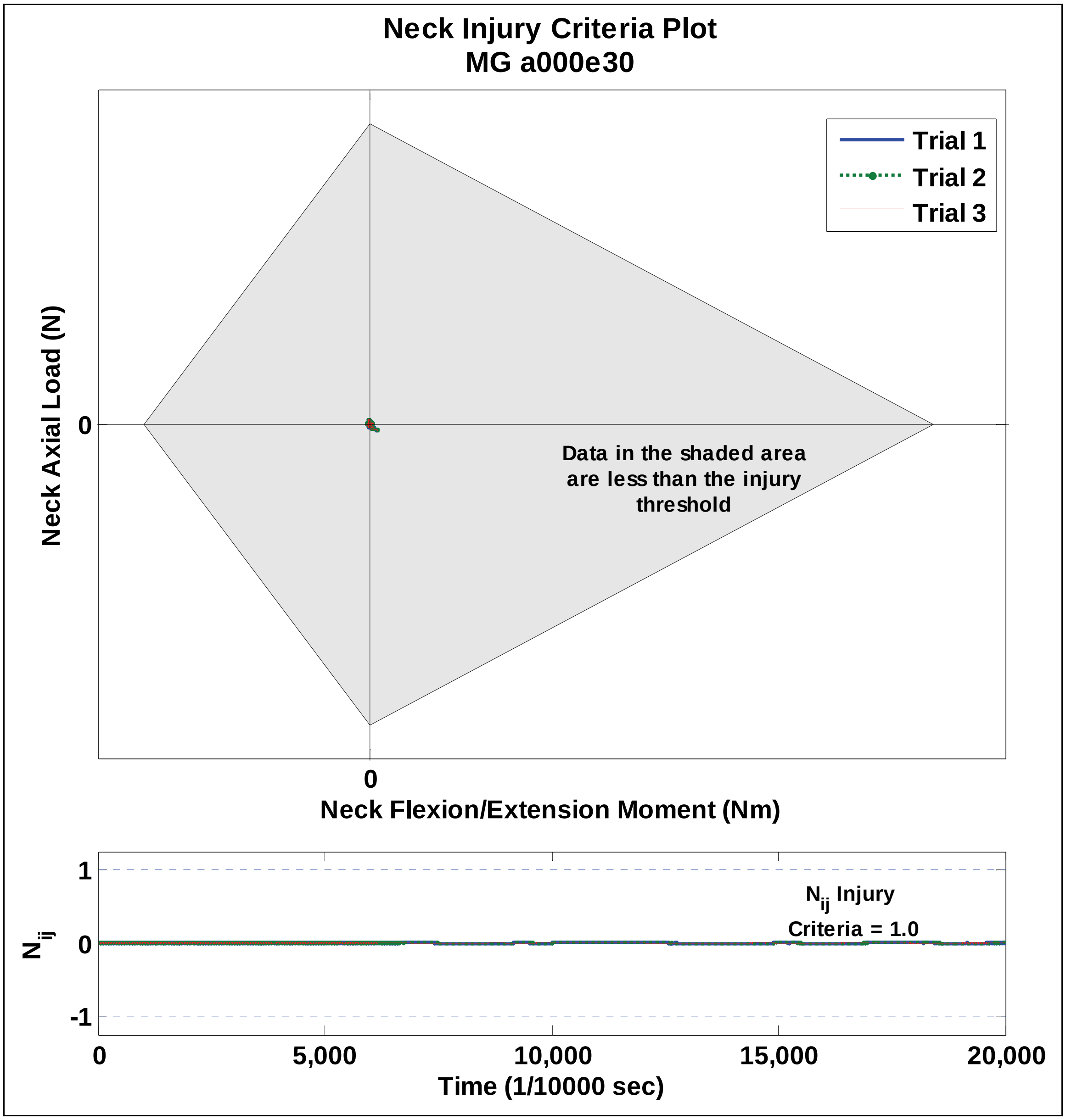

Figure 18. N_{ij} plot for gunner, azimuth = 0, elevation = 30.

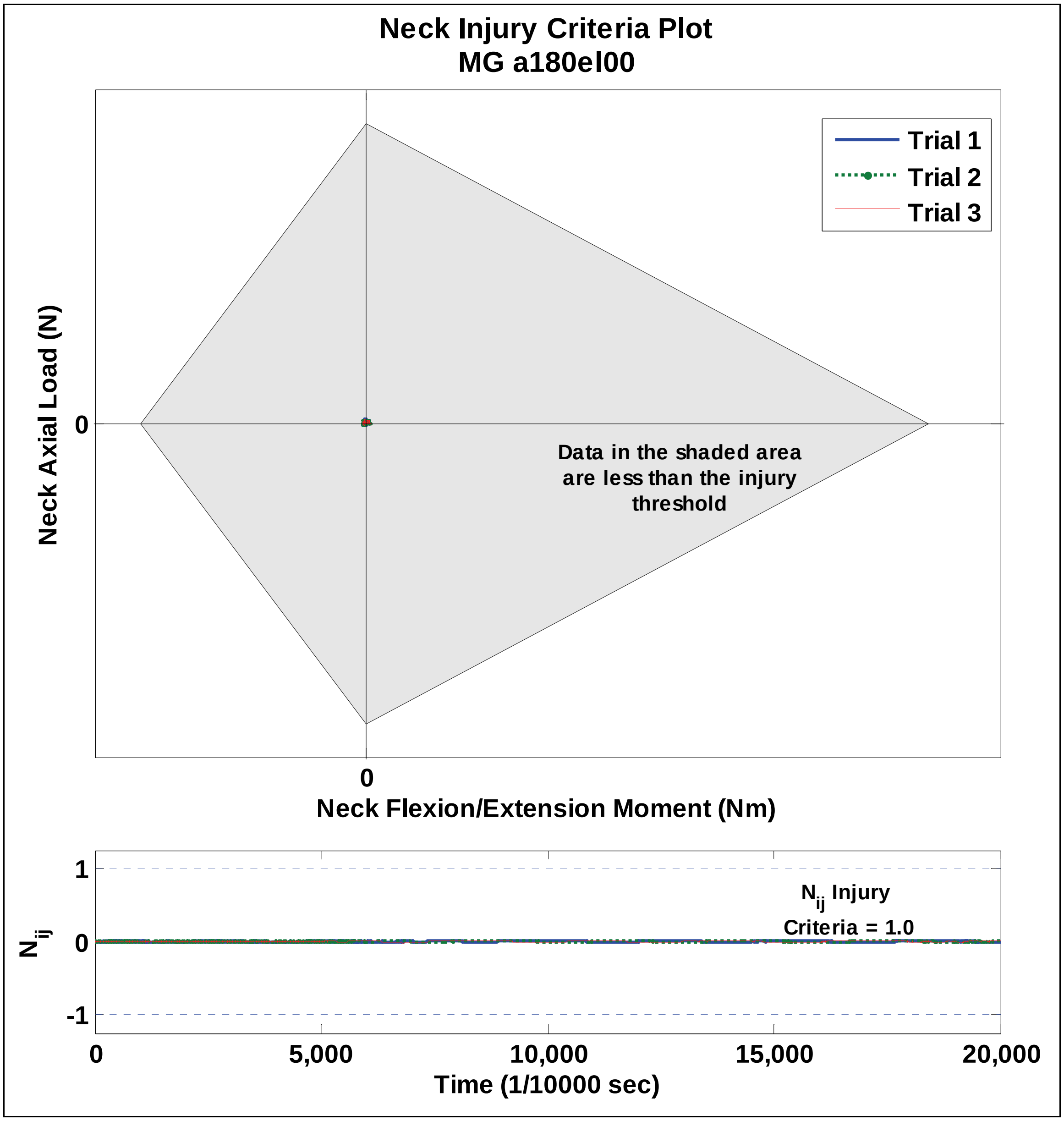

Figure 19. N_{ij} plot for gunner, azimuth = 180, elevation = 0.

7.3 Probability of Injury

The probability of head injury was calculated on the basis of equation 4 for the driver and gunner and was virtually zero for both the driver and gunner for every condition tested (see table 12), except the worst case scenario. Additionally, the probability of neck injury (and severity) was calculated with the equations in table 1 and is presented in tables 13 and 14 and figure 20.

Table 12. Probability of head injury.

Probability of Head Injury Based on HIC_{15} and HIC_{36}		
	HIC_{15}	**HIC_{36}**
Driver	1.3792×10^{-22}	1.0374×10^{-18}
Gunner	4.2476×10^{-23}	1.6043×10^{-19}

Table 13. Probability of neck injury based on N_{ij}: driver.

		Moderate					**Serious**				
		Azimuth Condition					**Azimuth Condition**				
		0	**45**	**90**	**135**	**180**	**0**	**45**	**90**	**135**	**180**
Elevation Condition	**-10**	0.132	0.129	0.129	0.128	0.127	0.050	0.048	0.048	0.047	0.046
	0	0.133	0.120	0.120	0.122	0.122	0.051	0.042	0.042	0.044	0.043
	10	0.117	0.117	0.117	0.116	0.115	0.040	0.040	0.040	0.040	0.039
	20	0.120	0.121	0.120	0.119	0.118	0.042	0.042	0.042	0.041	0.041
	30	0.129	0.127	0.126	0.127	0.124	0.048	0.047	0.046	0.046	0.044
		Severe					**Critical**				
Elevation Condition	**-10**	0.074	0.073	0.072	0.072	0.071	0.025	0.025	0.025	0.024	0.024
	0	0.075	0.067	0.067	0.069	0.068	0.026	0.023	0.023	0.023	0.023
	10	0.065	0.065	0.065	0.065	0.064	0.022	0.022	0.022	0.022	0.022
	20	0.067	0.068	0.067	0.066	0.066	0.023	0.023	0.023	0.023	0.022
	30	0.072	0.071	0.071	0.071	0.069	0.025	0.024	0.024	0.024	0.024

Table 14. Probability of neck injury based on N_{ij}: gunner.

		Moderate					**Serious**				
		Azimuth Condition					**Azimuth Condition**				
		0	**45**	**90**	**135**	**180**	**0**	**45**	**90**	**135**	**180**
Elevation Condition	**-10**	0.116	0.115	0.116	0.116	0.116	0.039	0.039	0.04	0.039	0.039
	0	0.126	0.126	0.126	0.123	0.119	0.046	0.046	0.046	0.044	0.042
	10	0.13	0.131	0.137	0.127	0.124	0.049	0.049	0.054	0.047	0.045
	20	0.126	0.127	0.128	0.125	0.124	0.046	0.047	0.047	0.046	0.045
	30	0.116	0.116	0.117	0.116	0.115	0.04	0.04	0.04	0.039	0.039
		Severe					**Critical**				
Elevation Condition	**-10**	0.065	0.064	0.065	0.065	0.065	0.022	0.022	0.022	0.022	0.022
	0	0.071	0.071	0.07	0.069	0.067	0.024	0.024	0.024	0.023	0.023
	10	0.073	0.073	0.077	0.072	0.07	0.025	0.025	0.027	0.024	0.024
	20	0.071	0.071	0.072	0.07	0.07	0.024	0.024	0.024	0.024	0.024
	30	0.065	0.065	0.065	0.065	0.064	0.022	0.022	0.022	0.022	0.022

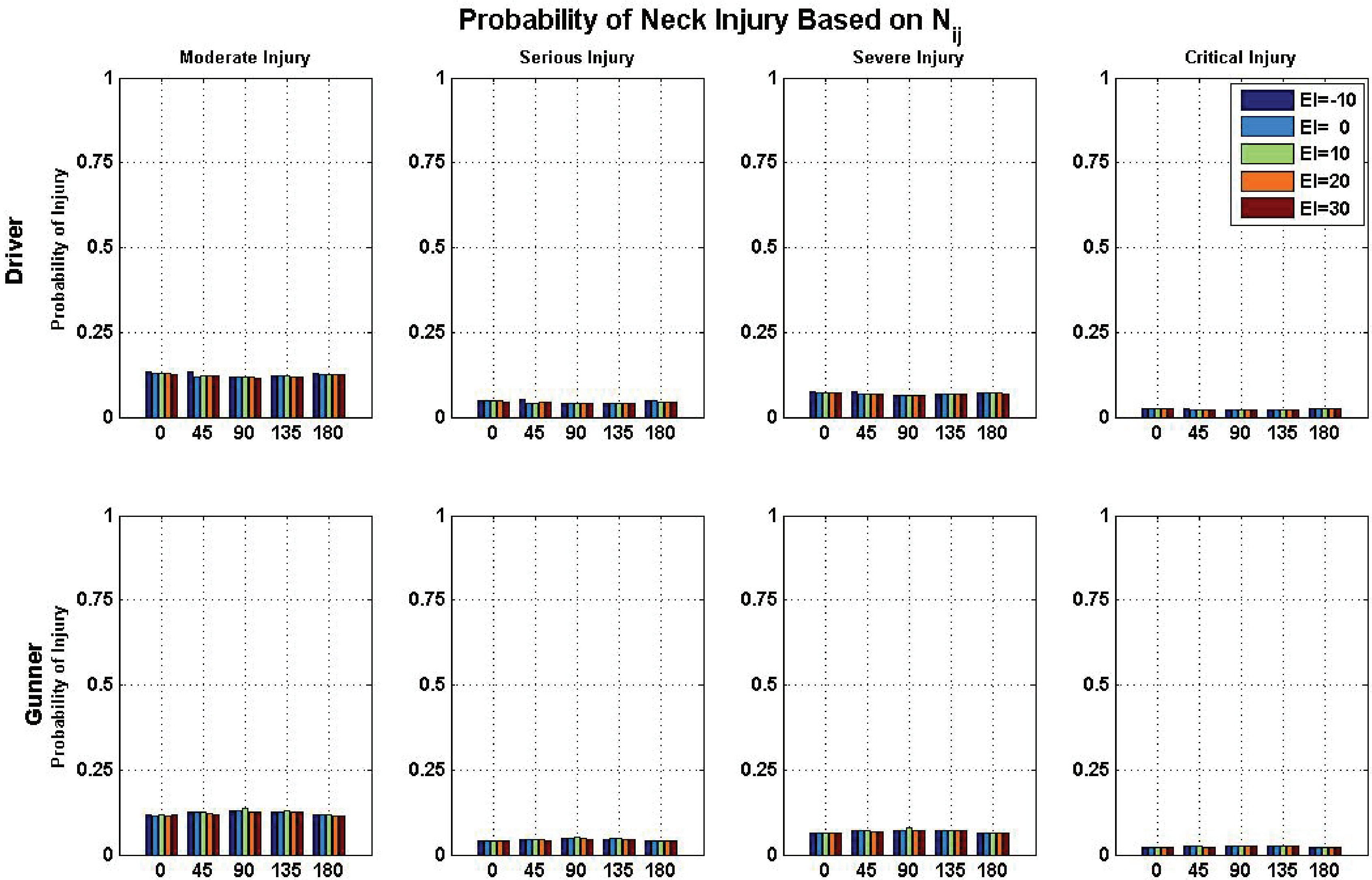

Figure 20. Probability of neck injury.

7.4 Worst Case Scenario Results

Data for the worst case scenario were only collected for the driver. The results for the HIC_{15}, the HIC_{36}, and the N_{ij} are presented in figure 21. All three measures were less than their injury criteria. Additionally, similar to the other conditions, the probability of head injury was virtually zero. However, the probability of moderate neck injury ranged from 0.116 to 0.12, indicating that between 11.6% and 12.0% of the time when the weapon is fired in this configuration, the driver will sustain a moderate neck injury. The probability of a critical neck injury ranged from 0.022 to 0.023, indicating that between 2.2% and 2.3% of the time the weapon is fired in this configuration, the driver will sustain a critical neck injury.

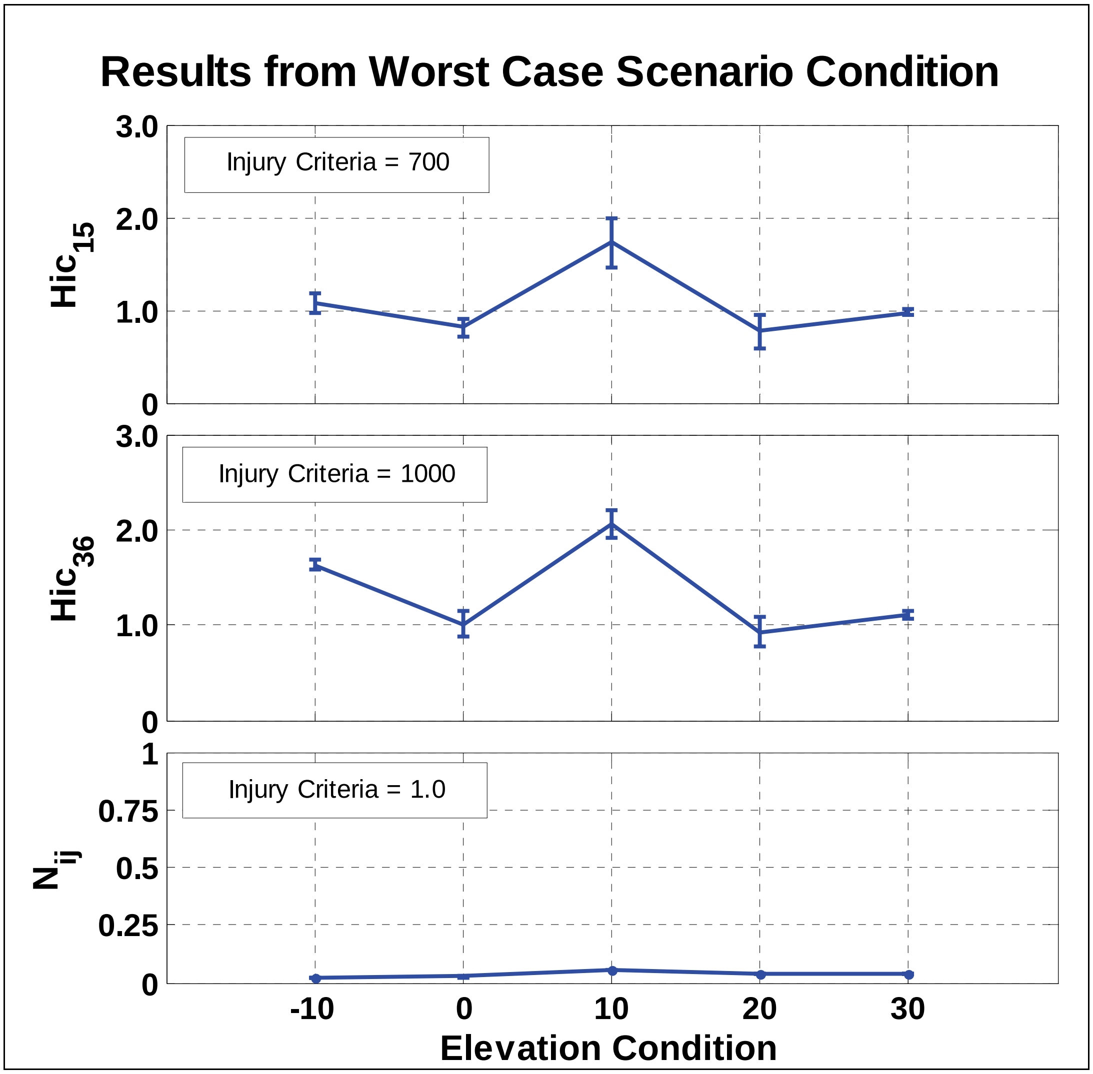

Figure 21. Results from analysis of worst case scenario.

8. Discussion

Our first objective was to quantify the effect of turret azimuth and elevation during weapon firing of an MCS on driver N_{ij}, HIC_{15}, and HIC_{36}. Pairwise comparisons between azimuth conditions reveal that changing the azimuth from 0 to 45 degrees results in a decrease in HIC_{15} and HIC_{36}; changing from 45 to 90 degrees results in an increase in HIC_{15} and HIC_{36}; changing from 90 through 135 and to 180 results in a decrease in both HIC_{15} and HIC_{36} (figures 2 and 3) for the driver. Additionally, pairwise comparisons between azimuth conditions reveal a minimum value for N_{ij} at the 90 degrees of azimuth condition (figure 7).

Pairwise comparisons between elevation conditions for the driver showed that increasing turret elevation resulted in a decrease in HIC_{15} and HIC_{36} between most conditions (table 3). Additionally, for the N_{ij}, statistically significant differences were found between all condition except the 0- and 10-degree conditions, the 0- and 20-degree conditions, and between the 10- and 20-degree conditions. While many of the differences found between elevation conditions were statistically significant, the differences were so slight that there likely is no operational effect between these conditions.

Our second objective was to quantify the effect of turret azimuth and elevation during weapon firing of an MCS on gunner N_{ij}, HIC_{15}, and HIC_{36}. Pairwise comparisons between azimuth conditions reveal an increase in HIC_{15} and HIC_{36} values between the 0 and 45 degrees of azimuth conditions, no statistically significantly differences between the 45 and 90 degrees of azimuth conditions, and a decrease in HIC_{15} and HIC_{36} between the 90 and 135 degrees and the 135 and 180 degrees of azimuth conditions for the gunner (see figures 11 and 12). Additionally, pairwise comparisons between azimuth conditions reveal an increase in N_{ij} between the 0- and 45-degree and between the 45- and 90-degree conditions, then a decrease between the 90- and 135-degree and between the 135- and 180-degree conditions. No statistically significant differences were observed between the 0- and 180-degree conditions (figure 16).

Pairwise comparisons between elevation conditions for the gunner showed no differences between the -10 and 0 degrees of turret elevation conditions. Further increasing the elevation of the turret resulted in a decrease in HIC_{15} and HIC_{36}, with the greatest differences occurring between the elevation = 10- and 20-degree conditions and between elevation = 20- and 30-degree conditions. The results showed no noticeable change in N_{ij} for the gunner when averaged across turret elevation conditions; however, because of the small standard errors of the mean, some of the differences between elevation conditions were found to be statistically significant. As with the driver, even though there were statistically significant differences between conditions, the differences were so small that there likely is not an operational difference between conditions.

NHTSA established and supports injury criteria for all three dependent measures (HIC_{15}, HIC_{36}, and N_{ij}). Values of less than 700 are considered less than the injury criteria for the HIC_{15}; values of less than 1000 are considered less than the injury criteria for the HIC_{36}; values of less than 1.0 are considered less than the injury criteria for the N_{ij}. Although there were statistically significant effects of azimuth and elevation and a statistically significant Azimuth x Elevation interaction on all three dependent measures, it is important to note that all the values for HIC_{15}, HIC_{36}, or N_{ij} were much less than the injury criteria established and supported by NHTSA.

Based on the HIC_{15} and the HIC_{36}, the probability of moderate head injury for the driver or gunner was very low. In contrast, the probability of moderate neck injury (based on the N_{ij}) for the driver and the gunner was about 0.13 (figure 20). This means that on average, 13% of the time when the MCS weapon is fired, the driver and gunner will sustain a moderate neck injury. Additionally, the probability of a critical neck injury for either the driver or the gunner was 0.023, meaning that 2.3% of the time when the MCS weapon is fired, the driver and the gunner can expect a critical neck injury. These results could be interpreted to mean that one in every eight firings of the MCS will result in a moderate neck injury, and 1 in every 43 firings of the MCS will result in a critical neck injury. Because the probability of injury is based on the N_{ij}, which is designed for single impulse events, it does not account for the cumulative effect of multiple impulses. These cumulative effects include issues such as micro-trauma to the neck structure and neck muscle fatigue that do not necessarily rise to the level of injury but may weaken the neck structure and result in a greater potential for injury in subsequent firing of the weapon. Micro-trauma to the neck and neck muscle fatigue may result in the potential for injury (when the weapon is fired twice) being greater than two times the potential for injury when the weapon is fired once. As a result, the actual probability of moderate neck injury for the driver and gunner of the MCS when the effect of cumulative impulses is considered is likely greater than 0.13. At the time this report was written, no standards for multiple impulse events had been established.

The worst case scenario was defined by the azimuth set to 150 degrees, the manikin restrained in a three-point harness, and the presence of a cupola to restrict head movement. For the worst case scenario, the probability of head injury based on the HIC_{15} or HIC_{36} was very low. Interestingly, in the worst case scenario conditions, the probability of neck injury was similar to the other conditions; the probability of moderate neck injury ranged from 0.116 to 0.12, indicating that between 11.6% and 12.0% of the time when the weapon is fired in this configuration, the driver will sustain a moderate neck injury. The probability of a critical neck injury ranged from 0.022 to 0.023, indicating that between 2.2% and 2.3% of the time when the weapon is fired in this configuration, the driver will sustain a critical neck injury.

9. Concluding Remarks

The goal of this study was to quantify the effects of turret azimuth and elevation on the forces, torques, and accelerations experienced by the vehicle's occupant during weapon firing. Based on the standards used by NHTSA, the acceleration of the head and the forces and torques experienced by the driver's and gunner's necks during weapon firing are less than the injury criteria for the 50th percentile male. Resulting injury rates were nearly zero for head injuries and were as high as about 0.13 (13%) for moderate neck injuries. The estimated probability of neck injury does not account for possible cumulative effects of the repeated impulses of the weapon firing. It is important to note that the injury criteria and probability for injury calculations were developed for single impulse events (such as a car accident) and may not be appropriate for multiple impulse events (such as the repeated firing of the weapon). Because of this and the fact that there may be a cumulative effect of repeated impulses on the probability of injury, the injury probabilities reported may be artificially low. At the time this report was written, injury standards for multiple impulse events had not been established.

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